LANDSCAPE

AS DEVELOPED BY THE PROCESSES OF NORMAL EROSION

by

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To the memory of
the illustrious
GILBERT, POWELL & DAVIS

Explanatory concepts are known through and through, fore and aft: the farther side of the concept of a ridge is seen just as well as the near side, by the eye of the imagination, which takes any point of view that it desires; the inside of the ridge is seen as well as the outside, the past and future forms of the ridge as well as the present form, for all these concepts are avowedly mental concepts only and not matters of fact.

W. M. DAVIS

PREFACE

This second edition of *Landscape* has been produced by arrangement with the Cambridge University Press, publishers of the first edition (1941). The book has been considerably enlarged and in part rewritten, and a number of new photographic illustrations have been added. Many of these are reproduced from Mr V. C. Browne's aerial photographs, while some are from photographs generously supplied by N.Z. Aerial Mapping Ltd. and the New Zealand Public Works Department, and others have been contributed by various correspondents. An attempt has been made to give credit to photographers wherever possible. The colouring of the frontispiece is an example of the artistic work of Mr V. C. Browne.

The plan of the book is very nearly the same as that adopted for the first edition, since the publication of which *Climatic Accidents in Landscape-making* has been published in 1942 and *Volcanoes as Landscape Forms* in 1944, completing a trilogy on landscape forms. The needs of students have been kept in mind, but not without an attempt to tell a continuous story that may be followed by general readers. The bibliographic lists now appended to the chapters are necessarily short and incomplete, but students using the book as a text will find that the majority of the books and articles cited are easily accessible in libraries.

Without elaboration I may reiterate the claim I made in the preface to the first edition that a reasoned understanding of geomorphic processes is a necessary part of the equipment of a geologist for the interpretation of geological history.

C. A. Cotton

Wellington
September 1947

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CHAPTER I

Introduction

THE STUDENT OF GEOMORPHOLOGY IS SO OFTEN CONFRONTED WITH THE results of atmospheric weathering, predominantly chemical, combined with downhill transportation of rock debris, largely facilitated by rain and running water, that he tends to separate these processes from all others. He is accustomed to think of them as "normal" as compared with others, which he places in a "special" category. These latter include the climate-controlled agencies, active in arid deserts, also glacial erosion, active at the present day only in restricted areas, and marine erosion, important only around the margin of the land. It is noteworthy that though certain commonly observed processes are termed "normal", it is not implied that others are "abnormal". As Fenneman observes, "The term 'normal erosion' is plainly open to criticism on the ground that one mode is just as normal as another, but no other satisfactory term has been proposed."

Normal processes develop normal landscapes, most of which present to the eye a succession of hill-and-valley or ridge-and-valley forms, and it is now universally recognised and regarded as a truism that the valleys have for the most part been excavated by streams of water that still flow through them. This explanation of the origin of valleys (and also of hills and ridges, which are merely the residual portions of the rock mass sculptured by erosion) gained acceptance, however, only in the nineteenth century. The arguments in favour of it were first clearly stated in 1802 by Playfair. Playfair relied for proof on what Davis has termed the *law of accordant junctions*, the principle of the adjustment of the gradients of tributaries so that

they make accordant junctions with the main valley—so "that none of them join the principal valley either on too high or too low a level".[1] Though exceptions to Playfair's law of accordant junctions may be found, they are all capable of explanation in such a way as not to contradict the principle.

Many rivers are guided, as will be shown in later chapters, by depressions of tectonic origin, that is to say, due to earth movements. Thus guided they proceed to erode valleys for themselves, and a tectonic depression after it has been modified in form by a river flowing through it is often called the valley of the river. Such valleys are not wholly the work of rivers, and some geomorphologists try to restrict the application of the term "valley" to the portion that is really the result of river erosion. Neighbouring mountain masses also are not wholly residual in that they do not owe their full heights to the excavation of valleys by erosion. These, however, are the major landscape features, and even where such forms are dominant there can be no doubt regarding the erosional origin of all the smaller valleys and the residual character of the hills, ridges, and spurs that separate them. "The mountains were not thrust up as peaks, but a great block was slowly lifted, and from this the mountains were carved by the clouds—patient artists, who take what time may be necessary for their work" (POWELL).[2]

Though some attention was paid by European geologists, notably by Rütimeyer,[4] to the principles and results of erosional degradation of the land, it was not until the seventies of the nineteenth century, the heroic period of scientific exploration of the American West, that a corollary to Playfair's law sometimes known as "Powell's law of base-levelling" gained acceptance.[2, 3] If sufficient time is allowed, the slopes of valley sides become more and more gentle, valley floors become broader and broader, and the intervening ridges and spurs become narrower and lower, and, as the material of the land above sea-level is gradually carried away, particle by particle, the whole surface is eventually reduced to very faint relief.

When the enormous age of the earth is taken into account, the fact that the land surface is not a continuous plain sloping gently to sea-level seems to contradict Powell's principle, but the explanation is that, from time to time, parts of the surface have been

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[1] See the list of references at the end of the chapter.

uplifted, so that the work of erosion has had to be begun afresh on them. Some parts of the earth's surface have been worn down almost to sea-level over and over again in the course of "geological time".

In studying landforms one must bear in mind that no feature of the surface is a finished product. The agencies that effect changes of form are everywhere at work: every part of the surface is even now undergoing change, and its future forms will differ from the present as the present differ from the past.

Little is known of the absolute rate at which landscape changes due to erosion proceed, though it is certain that the rate must vary within very wide limits—to some degree with different conditions of climate, and to a far greater extent with the varying degree of weakness of, or of resistance to erosion offered by, the rocks of the terrain. In the words of Powell,[3] however, "the higher the mountain the more rapid its degradation; . . . high mountains cannot live longer than low mountains, and . . . mountains cannot remain long as mountains; they are ephemeral topographic forms".

REFERENCES

1. J. Playfair, *Illustrations of the Huttonian Theory of the Earth*, p. 102, 1802.
2. J. W. Powell, *Report on the Colorado River of the West*, p. 204, Washington, 1875.
3. ———, *Report on the Geology of the Eastern Portion of the Uinta Mountains*, Washington, 1876 (see pp. 181-198).
4. L. Rütimeyer, *Ueber Thal- und Seebildung*, Basel, 1869.

CHAPTER II

Mass Movement of Waste

THE WASTE PRODUCED BY WEATHERING, MORE ESPECIALLY THAT resulting from chemical weathering, or "rock decay", accumulates on all surfaces except the steepest and forms the waste-mantle of soil and subsoil, the latter consisting of residual clay and partly disintegrated and decayed rock fragments. It is the presence of the waste-mantle that allows of growth of vegetation; and vegetation, when present, does its part in turn by helping to bind the waste, and by thus retarding its removal increases the thickness of the accumulation and makes possible the rounding and smoothing of hilltops and slopes of moderate steepness (Chapter XIV).

Though rock decay continues, the thickness of the waste-mantle does not increase indefinitely, for the waste, or, at least, its upper layer, is continually being removed by rain-wash and downhill creep, starting thus on its long journey towards the sea or some other resting-place, where it will sooner or later come to rest as sediment.

LANDSLIDES

More spectacular results are produced when gravity induces the sudden, or very rapid, precipitation of masses of waste and loosened rocks down slopes as *landslides.* These, though sporadic in occurrence and spasmodic in development, claim first attention as large-scale phenomena, and also because they are the direct and obvious causes of the formation of conspicuous landforms both in the scars left on the sides of hills and mountains and in the accumulation forms which result where the sliding, slumping, or streaming waste comes to rest. Into the scheme of the cycle of erosion, which will be developed in later chapters, these forms may be fitted as local and minor interruptions, and must be further regarded as locally developed initial forms on which the work of erosion must begin anew.

In *rock falls* and *rock slides* the displaced material consists almost wholly of loosened blocks of fresh or only slightly weathered

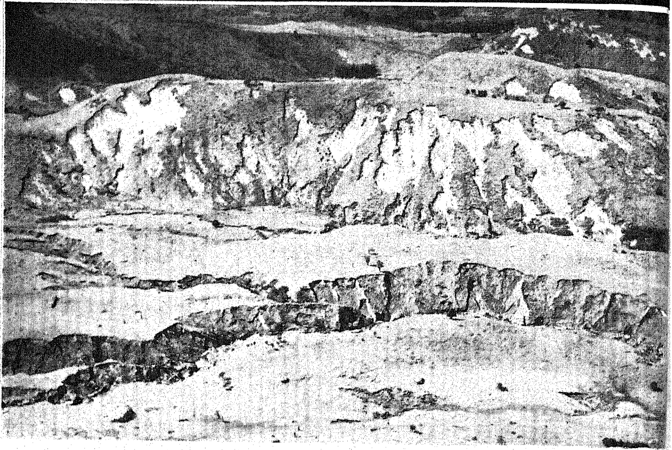
rock, but more frequently landslide or "slip" material consists in great part of the debris of rock decay. It may be relatively dry, but often contains much water, which, acting as a lubricant, facilitates the downhill movement. Saturation by unusually heavy rain, indeed, lubricating the material of the waste-mantle so as to overcome the friction that has been holding it in place on a slope against the pull of gravity is the commonest cause of initiation of movement. With complete saturation, sliding movement may be replaced by flow. Support at the toe of a slope having been removed by active erosion of some kind, downhill movement takes place when friction has been reduced to such an extent that it is no longer competent to hold the material, the trigger effect that sets a slip in motion being produced by unusually heavy rain, or perhaps by an earthquake.

In a *rock slide* (as defined by Sharpe[15]) the surface on which movement takes place is a bedding plane, major joint, or other plane of separation existing in the rocks, and is generally inclined somewhat less steeply than the average slope of the ground. The great rock slide known as the "fall of the Rossberg", a major disaster, which caused much loss of life and property in Switzerland in 1806, took place along a bedding plane in the rocks of the Rossberg mountain, and resulted in spreading a collection of huge blocks of rock over the Goldau lowland several miles away.

Usually on a smaller scale a *debris slide* (Sharpe) is a similar movement of the waste-mantle, which separates itself from a lubricated surface of the bedrock or the deeper subsoil (Fig. 1).

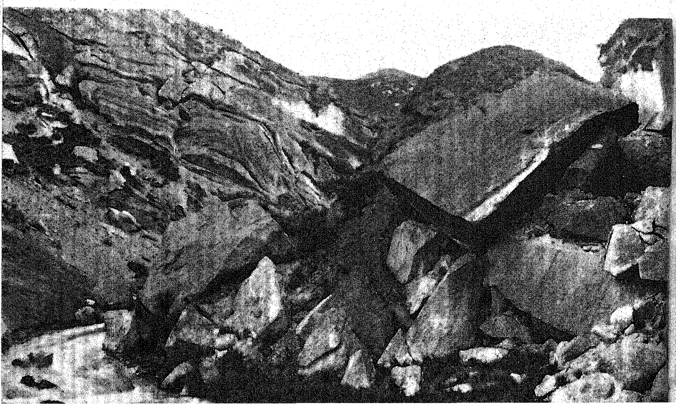
Rock falls (Sharpe), as their name indicates, are precipitated from cliffs or valley sides when these are sapped at the base by an undercutting agent such as a river (Fig. 2) or the sea, or when an earthquake occurs. They obviously do not depend on lubrication to the same extent as slides, nor is movement guided by an underlying slip plane.

Great rock falls, very extensive rock slides, and innumerable debris slides were set in motion by the New Zealand earthquakes of 1929 and 1931 in the West Nelson and Hawke's Bay districts. Every mountain side in the former district is now marked by numerous scars, where the waste-mantle and with it the forest covering have slipped away (Fig. 3). Similar scars have survived on the Rimutaka Range, near Wellington, since the earthquake of 1855.



N.Z. Public Works Dept., photo
Fig. 1. Scarred hillside eroded by debris-sliding, Hawke's Bay, New Zealand.

Fig. 2. Rock fall, Porter River, New Zealand. *Professor R. Speight, photo*



Slump Movement

In landslides of a *slump* character (Figs. 4-7), as distinguished from "slides", movement takes place on a *slip surface*, which is "typically deep-reaching and is a spoon-shaped surface or zone concave towards the slip" (Sharpe). The material moves "as a unit

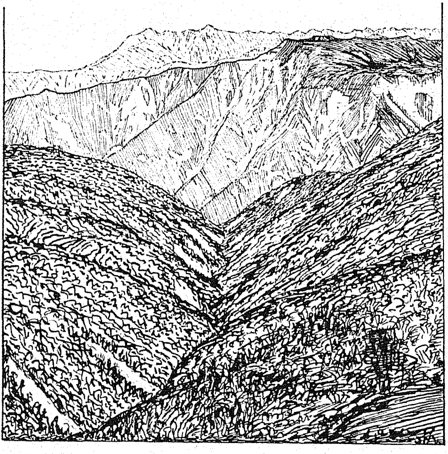


Fig. 3. Landslide-scarred mountain side, Karamea gorge, West Nelson, New Zealand. (Drawn by Dr J. Marwick.)

or as several subsidiary units, usually with backward rotation". This movement is of the nature of superficial gravity faulting. Curved branches from the slip surface commonly extend upwards, and so the slumped ground exhibits a terraced or stepped effect, with backward tilting of the steps that are formed at the surface where slumped strips have rotated somewhat as they have moved down the curved branches of the slip surface (Figs. 5-7). Slump movement may result in exposure of a great amphitheatre-shaped (or "spoon-shaped") scar in the landscape.

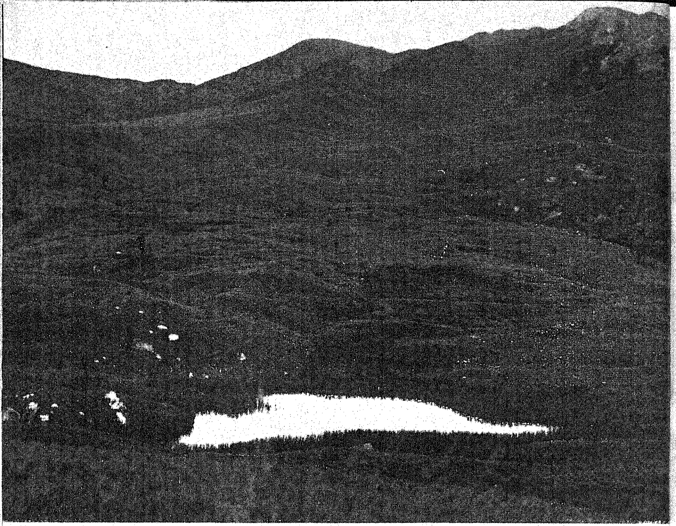


Fig. 4. Slump and earth flow, Motunau, New Zealand. *Professor R. Speight, ph*

In some cases slumping that does not extend beyond a shallow depth is indicated at the surface only by a series of slightly rotated narrow strips, termed *terracettes* (Sharpe). These are formed on slopes of 20° and even less of material that is thoroughly shattered and self-lubricated—like the "hydraulic limestone" of northern New Zealand, for example. This material is so unstable that the opening of road and railway cuttings is sufficient to cause whole hillsides to slump, even though the relief is small and all slopes are gentle.

Slumping of deeply weathered rocks forming the high walls of the Culebra Cut added greatly to the difficulty of excavating the Panama Canal. In the thickly loess-mantled Kansu province of China the whole face of the landscape was altered in many places by slumping of the loess on a vast scale in the destructive earthquake of 1920.

Accumulation Forms

Slump movement involves a forward horizontal thrust as an accompaniment of the subsidence at the rear, and, consequently,

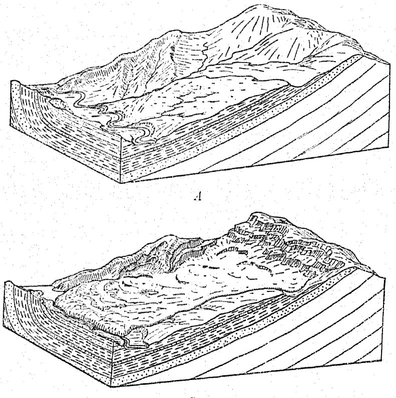


Fig. 5. Diagram of the Gros Ventre slide, Wyoming. *A* is a restoration of the former landscape; *B* exhibits slump and "earth-flow" features. (After Blackwelder.) (From *Geomorphology,* also by the author.)

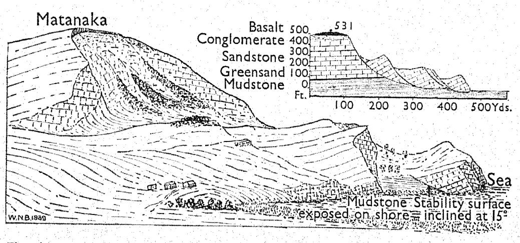


Fig. 6. Slump at Cornish Head, Waikouaiti, New Zealand. (Drawn by Professor W. N. Benson.) (From *Geomorphology,* also by the author.)

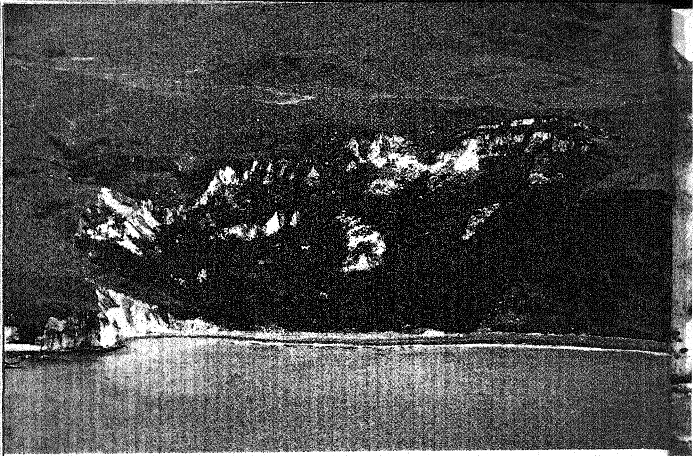


Fig. 7. Coastal landslide (slump) east coast of South Island, New Zealand. *V. C. Browne, p*

an upthrust or upwarped zone is found in some cases instead of heaped or streaming debris in front of the slumped ground. A striking example of this is afforded by the Whitecliffs slide, which (as interpreted by J. Henderson[8]) developed in front of a collapsing sea cliff, 1200 feet high, on the west coast of Nelson, New Zealand, as a result of the great earthquake of 1929. A part of the marginal sea floor 50 acres in extent, with its population of marine organisms, was thrust up to heights varying up to 100 feet above the sea.

The displaced material of a rock slide, even though dry, may be shot forward with such momentum as to spread it over a large area, burying vegetation, the habitations of men, and even pre-existing features of surface relief to a great depth, as in the case of the Rossberg-Goldau slide. In numerous places in the West Nelson district of New Zealand burial to a depth of 100-200 feet is recorded at distances up to a mile from the sources of the 1929 earthquake slides.

In the case of a slide of debris or of unconsolidated material saturated with water, the mobility may be sufficiently great to allow of flow down quite gentle slopes. The debris stream moves

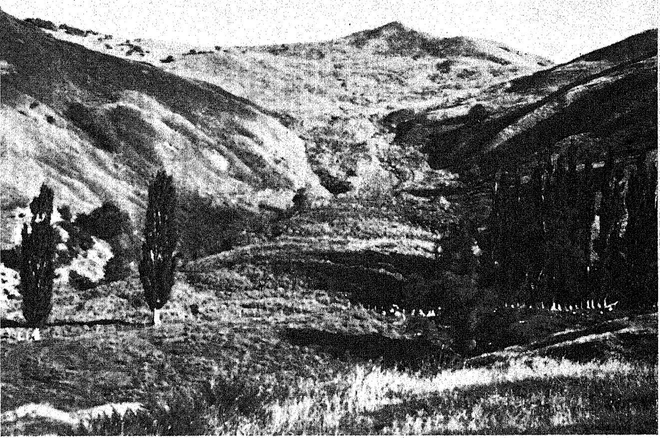


Fig. 8. Slump and earth-flow, near Tinui, New Zealand. *J. H. Sticht, photo*

forward with a rolling motion and sometimes with considerable velocity, spreads over low-lying and perhaps level ground far from its source, and comes to rest as a concourse of irregular ridges and hummocks somewhat resembling glacial moraines (Figs. 4 and 8). Undrained hollows among the hummocks may form tarns or small lakes.

Landslide Lakes

Larger lakes are formed when landslides block valleys and pond rivers (Fig. 9). Lakes held up by dams of loose debris are short-lived, for their overflow streams scour channels through the dams very soon after overflow takes place. Such bursting of landslide dams has been a frequent cause of disastrous floods in lower valleys. In the case of the Gohna landslide and temporary lake, formed in a Himalayan tributary of the Ganges in 1893, a barrier of debris 2 miles long and 800-900 feet high blocked the mountain valley in such a way as to form a lake in it 3 miles long. Though the river took eight months to fill the lake basin so formed, when it became

full to overflowing the outgoing stream cut a trench 400 feet deep through the dam in a few hours.

Numerous lakes were formed as a result of the rock falls and rock slides brought down by the 1929 earthquake in New Zealand. One, in the Matakitaki valley is 3 miles long, and took four days to

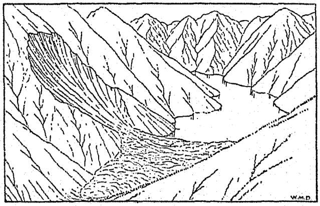


Fig. 9. A landslide lake in a mountain valley. (After W. M. Davis.) (From *Geomorphology*, also by the author.)

fill. Others, in the Maruia, Buller, and Mokihinui valleys had only short lives. The last-named was impounded by a dam 75 feet high and lasted seventeen days.

Some large lakes are held up by dams formed by ancient rock falls or rock slides blocking gorges. These accumulations consist of boulders and great blocks of hard rock, and have greater strength to resist scouring by river erosion than have those composed of weathered debris or other loose material. Such is the origin ascribed to the large and beautiful New Zealand lake Waikaremoana, 2015 feet above sea-level (Chapter V). The overflow channel from this lake descends 1200 feet in about 2 miles by the side of a great rock-slide dam of sandstone blocks, which has closed a gorge through a sandstone ridge. Water leaks through and gushes from many chinks in the dam.

Earth Flows and Mudflows

Earth flows (Sharpe) are landslides in which movement is so slow that the time occupied in attaining a new equilibrium may range from hours to years. An example is the Gros Ventre slide, in Wyoming (Fig. 5). Such movement takes place down gentle slopes. Superficial layers of waterlogged material may flow com-

pletely away from considerable areas—in some cases, as in examples in the St Lawrence Valley, in Canada, through bottle-neck outlets—to come to rest on adjacent valley bottoms, leaving extensive scarp-bounded scars. Incomplete outflow leaves slump features, including terracettes, within the scar boundaries.

Rapid and far-extending *mudflows* take the easiest courses down gullies and river valleys. They may travel many miles, temporarily filling the channels they follow to great depths with debris, though the flow passes on, and eventually comes to rest many miles from the source, and in some cases far out on gently sloping alluvial plains. They occur on steep slopes in some Alpine districts and, rather commonly, in semi-arid regions, where the surface is not bound and protected by vegetation. Mudflows also characterise some phases of volcanic activity. Originating at or near the summits of high cones, these "lahars" carry down the slopes not only volcanic mud but also great quantities of rock fragments, including some blocks of large size, and so mounds of volcanic boulders of all sizes may remain as hillocks, irregularly scattered or more regularly aligned in the direction of flow, after the finer material of the mud-flow has passed on or has been washed away (Fig. 10). In some semi-arid regions also successive mudflows have built up extensive superficial deposits of unstratified and unsorted material, which may contain very large boulders.[3]

Soil Creep

Less obvious than landsliding, but at the same time far more general, indeed almost universal, is an imperceptible downhill movement of the waste-mantle of slopes that is continuously in progress. Working along with surface wash, which is effective during heavy rains, this movement, termed *creep* by W. M. Davis, is the cause of migration of much waste to lower levels before it is eventually carried off by permanent running streams. The agency at work promoting creep is gravity, but creep has little else in common with flow, though the one may grade into the other. Small to-and-fro movements of rock and soil fragments in the waste-mantle are always taking place as the result of alternate heating and cooling, wetting and drying, freezing and thawing. Owing to the constant pull of gravity, there is a preponderance of downhill over uphill movement, and slow downhill creep results.

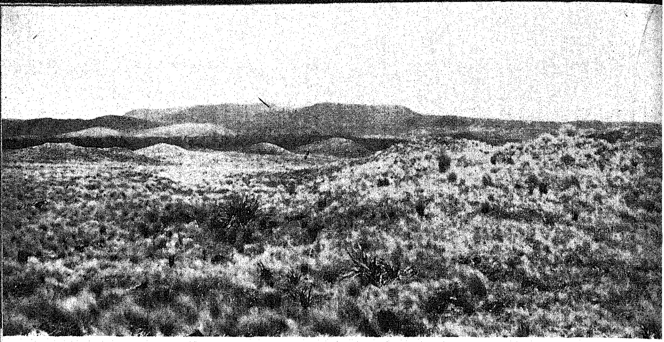


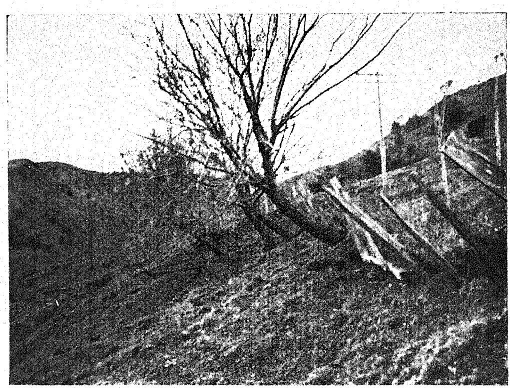
Fig. 10. A concourse of hillocks the cores of which are heaps of lava boulders believed to have been brought down from Ruapehu volcano, New Zealand, by a lahar (volcanic mudflow).

If expansion were equal in all directions, and extended indefinitely downward, the arrangement of the particles—or the structure of the formation—would not be affected; but dilatation is resisted in all directions except outward, and expansion in a single direction modifies the structure. The structure is again modified during the ensuing contraction, and during both changes gravity enters as a constant factor tending downhill. (Gilbert.)

Evidence of creep may be seen in the downhill sag of the edges of layers of partially weathered rocks, which Park[13] has termed "outcrop sag" or "curvature". Further positive evidence is found in the bending of tree trunks away from the vertical and the canting over of fence posts (Fig. 11), the partial closing of artificial trenches that contour a slope, and the sometimes obvious migration of rock fragments away from outcrops of the parent rock (Fig. 12).

Observers in regions with cold winters, who are familiar with the heaving of soil and subsoil due to frost, may be inclined to ascribe to frost action the chief rôle in promoting soil creep, but it cannot be the sole, and is perhaps not even the dominant, agency, as is witnessed by the evidence that creep is in progress in places where the soil is never frozen, as is the case in most parts of New Zealand.

Originating in association with soil creep there may be systems of small-scale terracettes, which may be taken advantage of by grazing animals and be used by them as paths. It has been



J. H. Sticht, photo

Fig. 11. Soil creep carrying trees and fence posts downhill, Mangapakeha Valley, New Zealand.

suggested that development of all sheep-track patterns is controlled by backward tilting, or rotation, of small turf-covered soil blocks along curved surfaces.[12] Most sheep tracks, however, are worn paths of bare ground cut by the hooves of grazing animals and scoured to some extent by rain wash. To what extent "the continued walking of cattle [or sheep] on hillside paths will aid the development of small slip planes", as Sharpe[15] suggests, and so assist the mass movement of waste remains problematical. Sheep tracks are

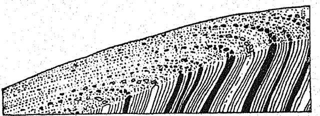
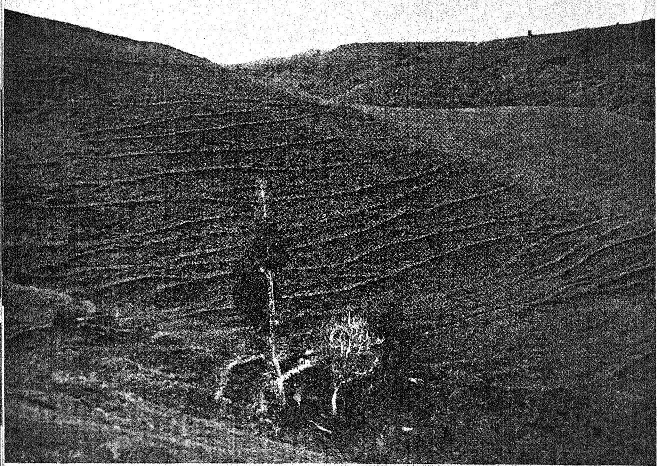


Fig. 12. Diagram of downhill creep of waste. (After Davis.)
(From *Geomorphology*, also by the author.)



Professor J. A. Bartrum, ph

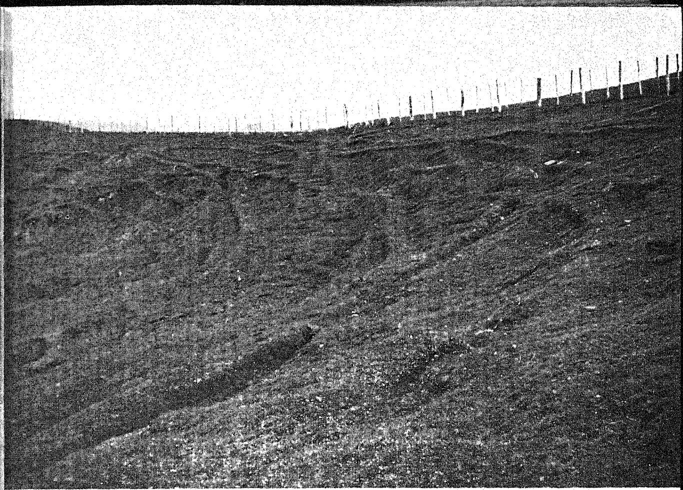
Fig. 13. A normal sheep-track pattern in the Auckland province of New Zealand.

cut very rapidly, however, as may be seen where they are present on fillings recently tipped in the course of highways improvement in New Zealand, and normal sheep-track patterns (Fig. 13) afford no indication that their formation has led to any appreciable slumping. Naturally, terracettes, where they are present, are used also as paths by animals (Fig. 14).

Talus Slopes

Downhill movement on screes or talus slopes takes place in part by creep (*talus creep* or *rock creep*), but there may be also much streaming and rolling of material down the surface slope as down a chute. The source of supply of the usually angular scree material is most often a bare-rock cliff or sharp mountain crest that is undergoing mechanical weathering of the spauling type, or perhaps exfoliation.* The supply may be limited, if the outcrop from which

* Phases of mechanical disintegration recognised by A. C. Lawson[11] are: "(1) Development of joints; (2) exfoliation in broad slabs . . . ; (3) spauling, due to ruptures necessary for the relief of strain; (4) granulation, particularly exemplified in certain coarse-grained granites; and (5) slacking, as exemplified by shale."



Professor J. A. Bartrum, photo

Fig. 14. Terracettes in the same locality as the sheep tracks shown in Fig. 13.

it is derived is small, or may be almost inexhaustible. Being built by constant addition to its surface of rock waste glissading or streaming down, a talus slope may grow to such dimensions that its base covers all the available ground. If it is still abundantly fed from above, it will serve thereafter as a chute, delivering waste at the toe of the slope for transportation by a river or glacier or to be broken up and removed by the waves of the sea. "Unless constantly fed from above," however, "the angle of slope of the talus will fall below the maximum angle of rest* as a result of the combined work of weathering and creep" (SHARPE). Weathering then begins on the surface and some soil is formed, the slope becomes (under

* "The angle of slope of a talus is determined in part by the kind, shape, and size of the rock fragments of which it is composed. If there is a constant and abundant 'dribble' of rock from above, the upper part of the slope will stand at the maximum angle of repose for the given conditions—usually between 26° and 36°. The term *angle of repose*, or *angle of rest*, however, is ambiguous because it has been used to mean not only the angle at which a stable mass of unconsolidated material will begin to move but also the somewhat lower angle at which such a mass in motion will come to rest. The angle at which rock waste accumulates on a talus approaches the higher of the two." (SHARPE.)[15]

favourable conditions of climate) more or less completely covered with vegetation, and future downhill movement is of a similar nature to that on slopes of weathered waste overlying bedrock.

Solifluxion

In climates so cold that freezing and thawing of the ground occur frequently rock debris creeps rapidly down even quite moderate slopes. In winter the ground is hard-frozen in sub-Arctic lands, and in summer it remains frozen at some depth, but in a superficial layer kept saturated by water supplied by the melting of winter snows and of the frozen ground (or *tjaele*) frequent freezings cause "frost heaving", which is in part a result of the expansion of water on freezing but is due in greater degree to the growth of ice crystals formed of water drawn towards the surface by capillarity.[16] Under Arctic and especially sub-Arctic conditions processes associated with frost heaving induce *solifluxion*, a rapid down-slope creep that affects the residual weathered layer and all other superficial debris that contains a large proportion of fine material. Movement takes place down slopes of very gentle declivity. True solifluxion seems to be almost, if not altogether, confined to a superficial layer softened by summer melting (and remaining saturated with melt-water) over perennially frozen ground.[17] The process is described by Andersson[1] as a "slow flowing of waste saturated with water" and by Antevs[2] as "a viscous flowage of . . . clayey debris" which carries blocks along with it; but according to Taber[17] it is essentially a rapid soil creep activated by the "thrust and heave of frost action".

Stone Rings and Polygons

On quite horizontal ground, notably in Spitsbergen, patterned ground results from frost heaving. The most conspicuous features (*stone rings* or *polygons*) are formed where large stones have apparently been thrust outward from evenly spaced centres to form low ridges that arrange themselves so as to enclose circular or roughly hexagonal areas (Fig. 15, A). Within each such cell the ground is slightly domed and consists of either quite fine material or of a mixture of small rock fragments and fine material. A ring diameter of 6 to 8 feet is common, but where the blocks of rock are unusually large the rings are large also, with a maximum diameter

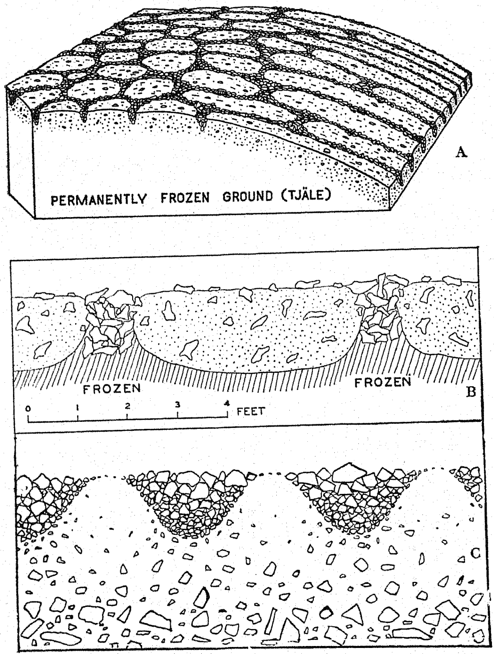


Fig. 15. *A*: Stone rings or polygons and stone stripes. (After C. F. S. Sharpe.) *B*: Cross-section of stone stripes developing on the St Elias Range. (After R. P. Sharp.) *C*: Cross-section of miniature stone stripes (striated soil) in New Zealand. (After Zotov.)

of about 30 feet. In fine material, on the other hand, they are quite small; and many patterns of miniature polygons less than a foot in diameter are found in the temperate zones on cold upland surfaces that have recently been depleted of vegetation and thus

subjected to soil erosion. It is generally held that large-scale stone polygons are developed only over permanently frozen ground, but this is not a necessary condition for miniature forms, patterns of which are now forming over unfrozen subsoils.[2, 17a]

Debris like that which forms polygons if creeping downhill develops *stone stripes,* a pattern in which parallel strips of stones and of finer debris are aligned in the direction of steepest slope (Figs. 15, 16). This pattern is clearly of similar origin to that of polygons, for gradation from one to the other through an elongated mesh pattern is found where there is a change of slope (Fig. 15, A). Miniature stone stripes, of dimensions comparable to those of miniature polygons, are called "striated soil" by Zotov.[18] According to Zotov the dimensions of polygons and striae "appear to depend on the coarseness of the material and the depth of freezing—i.e. on the severity of frost". Investigation shows that the undersurface of a coarse stripe is sharply defined and that it has fine material under it (Fig. 15, C).

Under sub-Arctic conditions a very large proportion of the product of frost shattering and weathering eventually becomes finely pulverised by the continued activity of frost, but some of the larger blocks of rock survive and remain embedded in mud. Hamberg[7] and Taber[17] have explained a mechanism, termed "upfreezing" by Antevs,[2] by means of which the process of alternate freezing and thawing thrusts blocks to the surface and right out of the ground; and both Antevs and Taber find in such rejection of blocks and the consequent sorting of materials by frost action an explanation of the much discussed processes that make stone rings and stripes. (The many theories have been stated briefly by Elton.[6]) As regards stone rings, Taber has observed that low mounds, "frost boils" as he terms them, develop at favourable points (generally at equal distances apart). "Repeated freezing and thawing bring large fragments to the surface and then move them gradually downward and outward from the top of the boil. Fragments move outward because of overturning when heaved above the surface and because of the growth and melting of ice crystals beneath them. . . . The radial migration of coarse material from closely spaced frost boils on a level or gently sloping surface forms a polygonal network pattern." Various authors agree in attributing movement of blocks outward from centres towards accumulating ring ridges in some

R. P. Sharp, photo

Fig. 16. Large stone stripes on the St Elias Range. The coarse stripe is about 5 feet wide, and the large blocks are 2 to 3 feet in diameter.

way to alternate expansion and contraction of the columns or cells of fine material within the rings, assisted by gravity.[2]

Rings or polygons of coarse fragments will when once formed tend to concentrate frost action within the cells they enclose; and so the sorting process will continue. The breaking down of larger fragments within the cells by frost action will also increase the proportion of mud.[9] "This condition . . . may be the cause of peculiar absence or scarcity of medium-sized stones in stone nets and stone rings" (ANTEVS).

The mechanism of formation of miniature stripes and polygons must be similar in a general way to that which produces the larger-scale phenomena, but it apparently achieves results very rapidly and is related to frost action in a thin superficial layer of soil over ground that is not permanently frozen. Zotov,[18] discussing the development of miniature forms, points out that when some concentration of the larger fragments into superficial rings or stripes has taken place (Fig. 15, C) these are thenceforward less subject to frost heaving than the adjacent areas composed of finer material, which is "better able to hold capillary water" and is upheaved by every frost. It continues to eject such coarse fragments as have remained embedded in it.

Mud Polygons and Earth Hummocks

Another pattern seen on level ground in sub-Arctic regions is a regular system of low mounds of even size (but on different scales in different places). Where consisting of bare "soil" these have been called "mud polygons" and where turf-covered "earth hummocks". They are separated by furrows in regular polygonal patterns, though without a meshwork or lines of stones. "Earth stripes" of related origin appear on some slopes. These patterns are attributed by Elton[6] and Sharp[14] to frost heaving, which progressively pumps up the soil at regularly spaced points.

Block Fields

A *block field* is a field of angular blocks produced largely by frost shattering of resistant bedrock on a mountain top. In some cases the process of alternate freeze and thaw seems to be moving the loosened blocks so that they tend to creep down slopes. Strictly this is an "autochthonous" felsenmeer (Högbom). More extensive block fields on lowlands in Arctic regions have accumulated as a result of downhill migration of loosened blocks. Such migration has taken place perhaps by solifluction, but if so, much fine material formerly present, which has made solifluction possible, has been washed away by flood waters from among the blocks after the mixed debris has come to rest. Similar accumulations along the axes of valleys in the Falkland Islands which are termed "stone rivers" seem to be of like origin.

Rock Glaciers

Stream-like, in some cases elongated and branching, accumulations of coarse blocks obviously derived from the heads of mountain valleys that contain them are termed *rock streams* and also *rock glaciers* (Capps[4]). Chaix[5] has found that most steep rock streams no longer move perceptibly but that some, which consist superficially of similar coarse blocks but have gentler slopes than the immobile streams, move like glaciers. His explanation of this different behaviour is that the mobile streams (rock glaciers) contain much mud, which has accumulated in the interstices between rock fragments in a sub-surface layer after being carried in by water, and that this mud flows, or creeps, when affected by alternate freezing and thawing, carrying with it the superficial layer of clean blocks. In typical rock glaciers glacier-like tongues of blocks seem to be thrusting, or to have thrust themselves, forward and to have thus developed wrinkles of the surface parallel to the front and sides of the tongue.

Both rock streams (relatively smooth and steep) and rock glaciers are explained by Kesseli[10] as fossil glaciers in which movement has now ceased owing to the melting away of true glacier ice formerly present along with very abundant rock debris; but this explanation cannot be applied to examples like the rock glacier of the Val Sassa (Engadine) which is still moving with an appreciable velocity if, as Chaix[5] maintains, these contain no glacier ice.

Periglacial Surface Forms

Solifluction or rapid creep, aided no doubt by small mudflows, results in the development of many irregular terraces on slopes in sub-Arctic ("low" Arctic) climates all of which seem to be formed as a consequence of rather slow migration of a surface layer over frozen ground. "Turf-banked" benches[2, 17] are discontinuous, with lobate fronts, and are formed where downhill movement is checked or arrested by mats of vegetation. Movement ceases, according to Taber, if the mat becomes so thick that thawing does not penetrate through it. "Stone-banked" terraces (Antevs) or "stone garlands" (Huxley and Odell[9]) are of similar form, but, according to Sharp,[14] the latter are of different origin, the term being applicable to forms transitional between stone rings and stone stripes. Stone-banked

terraces and the larger-scale forms termed *altiplanation terraces* (Eakin) are banked against ramparts of blocks the building of which Taber[17] describes as follows:

Large rock fragments [such as are liberated by upfreezing] move downslope faster than the underlying fine soil. . . . The downward movement may be checked by change in slope, by insufficient fine soil to prevent the blocks from coming in contact with one another and with the underlying bedrock or frozen ground, and by vegetation. . . . Their accumulation forms a retaining wall . . . and fine material is gradually washed out of the interstices. When small the embankment may move *en masse*. . . . When it becomes larger its resistance to movement increases. . . . The embankment then tends to advance and grow in height because of the addition of blocks to the scarp.

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CHAPTER III

Rain and Rivers

RUNNING WATER IS THE MOST IMPORTANT OF THE AGENTS RESPONSIBLE for the shaping of the land surface by erosion under "normal"—that is to say, humid and warm or temperate—climatic conditions. Most English and American writers use "erosion" as an inclusive term, for which "denudation" is a synonym. Some geomorphologists of the German school, however, distinguish between "denudation", defined as "degradation by surficially extensive mass movements" (C. SAUER), and "erosion" or "linear erosion" (corrasion). Streams and rivers transport seaward the debris from the whole landscape and, at the same time, do an important share of the work of valley excavation, while the run-off of newly fallen heavy rain as rills and flowing films of water removes fine soil particles, co-operating thus, as *rain-wash*, with other agencies in the general wastage and lowering of the land surface.

RAIN-WASH

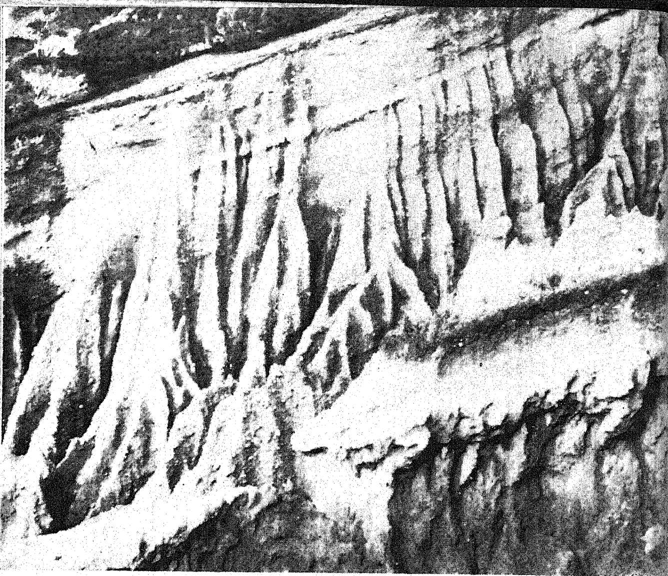
Heavy raindrops as they fall loosen particles of fine waste and take the material into suspension as mud: they thus facilitate its removal by rain-wash. Especially when the soil and subsoil are already saturated by continued heavy rain, a network of rills or a continuous water film, or sheetflood, may develop even on convex upper slopes, picking up and carrying off fine soil particles, delivering them presently into more concentrated though ephemeral streams in the gullies, which are the feeders of more continuously flowing rivers. Raindrop impact is effective only on bare ground, but the rills and sheetfloods formed during heavy rain may rob soil particles even from ground with a protective covering of vegetation, and this type of erosion of the waste-mantle must be at work over a great proportion of the land surface. It is not easy, however, to find positive evidence in demonstration of the process, and the argument for its universality depends on the prevalence of convexity of summit forms in most landscapes, in the development of which this

process, according to Lawson's hypothesis (Chapter XIV), plays an important part.

Badlands

The effects of *raindrop impact* and of scouring by concentrated wash in places where the run-off is gathered quickly into definite streams are more easily demonstrated. Both are conspicuous on outcrops of sandy clay where these are bare or only sparsely protected by vegetation, as is the case in semi-arid regions, in the vast areas of "badlands", for example, in the western interior of North America. *Badland* erosion is rare in the natural landscape under normal humid conditions, however, though it may appear as a result of deforestation or of overstocking on hilly pasture land. The close texture of clay causes an immediate run-off of nearly all the water that falls upon it as heavy rain. Gathering in close-set rills this water scours channels, especially if some sand particles are present mixed with the clay to act as cutting tools, and a miniature landscape of innumerable closely spaced steep-sided valleys and ridges is thus developed by stream sculpture. The conditions for development of badland forms may vary considerably, as is shown by the fact that they are not confined to sandy clay terrains but make their appearance occasionally also on surfaces underlain by gravel (Fig. 17).

Some land surfaces from which rain-wash (assisted by raindrop impact) is engaged in removing fine soil particles are littered with residual boulders, small or large. Most of these have been rounded by *spheroidal weathering* before becoming exposed at the surface as a result of removal of the surrounding finely weathered waste, but still retain hard cores that are in many cases scarcely affected as yet by rock decay. Their rounding has been an effect of truncation of the edges and angles of subsurface joint-bounded blocks as the processes of chemical decay have worked inwards towards the core of each block from intersecting flat-joint surfaces. Once the original corners have been rounded off in this way, successive concentric layers have been shed by exfoliation due mainly perhaps to volume changes accompanying hydration of silicate minerals in the process of chemical weathering, and thus the dwindling cores of still unweathered rock may have become almost spherical.[1] Igneous rocks with abundant silicate minerals are perhaps the most



F. H. Clift, photo

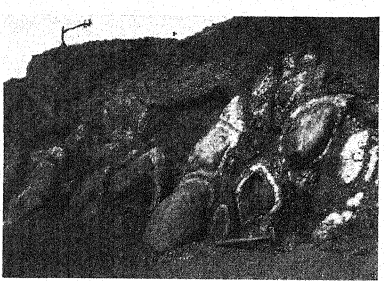
Fig. 17. Badland erosion on partly consolidated gravel, White Bluffs, Marlborough, New Zealand.

susceptible to spheroidal weathering (Fig. 18), but feldspathic sandstones are also frequently affected. Accumulations of boulders of this origin on upland surfaces have often been mistaken for alluvial deposits of water-worn cobbles or coarse gravel, and even for glacial moraines.

Tors on plateaux and uplands on granite terrains (Fig. 19) are scattered or piled boulders of similar origin but of large size. In some cases the boulders have been very incompletely rounded by subsurface weathering, though undergoing further rounding and reduction in size by physical weathering after exposure. The cores of the great granite blocks appear to have lain between joints in a widely spaced pattern. The well-known tors of Dartmoor take the form of piled groups of boulders with horizontal extension that suggest architectural effects; and rectangular tors, still attached to

bedrock, occur at very frequent intervals all over those parts of the flat-lying mica-schist terrain of the South Island of New Zealand that are situated in the semi-arid inland district, where, apparently, the finely disintegrated soil in intervening areas has been removed in the past by rain-wash. Now, since the natural vegetation has been depleted, wind also is taking part in this process.

Parts of the central African plateaux that are underlain by granite rocks are heavily encumbered with huge boulders disrupted and



M. Ongley, photo

Fig. 18. Sub-surface weathering has developed spheroidal cores in basalt, Mosgiel, New Zealand.
(From *Geomorphology,* also by the author.)

exposed by weathering and rain-wash; and unglaciated parts of the granitic highland surface of the Sierra Nevada of California are completely covered by a "veneer of loose blocks" so thick that it swallows all surface water and prevents the formation of running streams.[3] This constitutes an autochthonous felsenmeer.

Earth Pillars

Raindrop impact is effective on all unprotected surfaces of weathered or unconsolidated fine material, but only rarely is a yardstick available to make possible an estimate of the rate at which material has been loosened by this agency and removed. Certain textures and structures in the materials undergoing erosion, however, favour the survival of residual forms that give some idea of

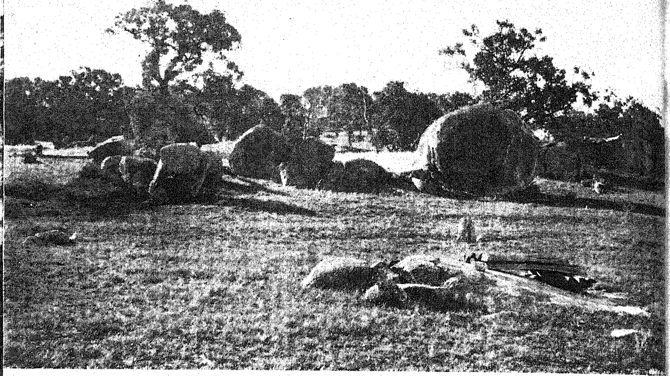
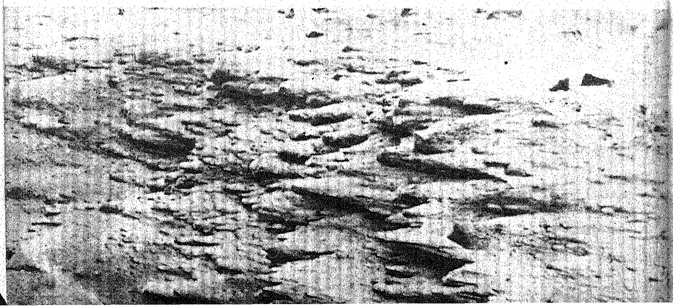


Fig. 19. Residual boulders of granite forming tors, New South Wales.

the depth of erosion, though rather exceptional conditions are required for the perfect development of these. The picturesque minor surface-relief forms termed *hoodoo columns* and *earth pillars* are slender residual columns of unconsolidated sediment or waste of a kind susceptible to rapid erosion by rain, which are capped or roofed by slabs or boulders of resistant material in such a way that they have escaped the effects of general lowering of the ground level by erosion. Hoodoo columns are capped by surviving relics of thin hard layers in horizontally bedded formations. Some such

Fig. 20. Horizontal "earth fingers" cut by wind-driven rain, Breaker Bay, Wellington, New Zealand



features no doubt originate also by processes of stream erosion, and they grade into the larger table-topped forms developed in the course of the cycle of erosion in such materials and structures.

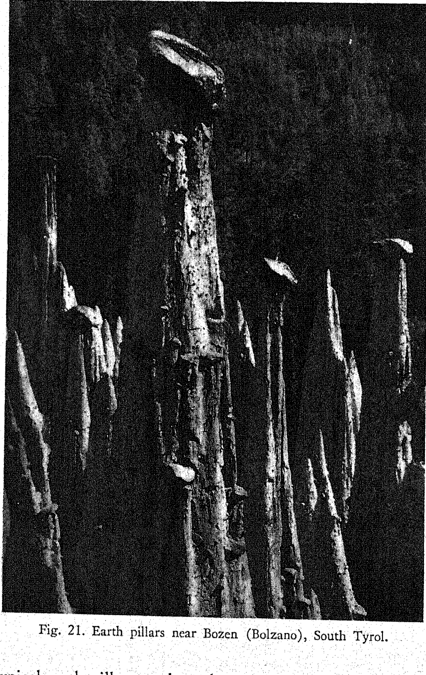


Fig. 21. Earth pillars near Bozen (Bolzano), South Tyrol.

Typical earth pillars, such as those in upland valleys near Bozen (Bolzano), in South Tyrol, are capped by boulders. In the Tyrolese examples the material composing them is a glacial deposit con-

sisting of rock fragments, with a clay matrix, and containing scattered boulders, some of which are of considerable size. An illustration of the efficiency of erosion by wind-driven rain is afforded by nearly horizontal "earth fingers", as they may be called, near the "windy city" of Wellington, New Zealand (Fig. 20). The material which locally favours their formation, and which is exposed in a road cutting that acts as a wind funnel, is a sandy clay derived by weathering from feldspathic blown sand, and there is an admixture with this of small rock fragments derived from adjacent outcrops, which protect the "finger tips". High columns (Fig. 21) can be developed only in windless situations, for wind-driven rain would undercut and destroy them. Indeed, the stronger the wind the more effective is raindrop impact.

Ground Water

Wet-weather rills and sheetfloods, the immediate *run-off* from the surface, feed the ephemeral streams that flow in gullies, and these are tributary to more permanent streams or rivers and furnish a part of their flow. Permanent streams, however, draw a great part of their supply of water from the ground. Part of the water that falls as rain, but, of course, a very variable proportion of it, does not run off immediately, but sinks, or infiltrates, into the ground. A certain amount of this water is returned to the surface by capillarity, and evaporates either directly or through the leaves of plants, but much of it, after sinking through the unsaturated and generally weathered surface material, joins a continuous body of *ground water* extending down to a variable depth governed by the extent to which downward percolation can take place through bodies of porous or creviced rock. This ground water is the sole source of supply of water to permanent streams in dry weather, and some streams are drawing from it at all times, though leakage of water through stream beds to join the ground water takes place also under certain conditions.

The ground water has a definite upper surface, the *ground-water level*, or *water table*, which rises and sinks in wet and dry seasons, and may reach the land surface after a prolonged spell of wet weather. Its lowest position sets a limit to the depth of chemical weathering. On the banks of permanent streams the water table reaches the land surface and coincides with the surface of the

flowing water (Fig. 22). The ground water moves slowly through the pore spaces between the grains of open-textured rocks, and through fissures in more compact and impermeable rocks, seeking an outlet at a lower level. Barriers of impermeable rock may cause the water table to intersect the land surface on hillsides, so that springs result, but this is rather exceptional, and normally the water finds a way of escape by seepage along the beds and sides of streams

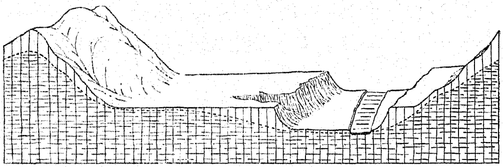


Fig. 22. Diagram showing the ground water (shaded), and the water table (the broken line).
(From *Geomorphology*, also by the author.)

below the level of the running water. Owing to friction of the narrow passages through which ground water makes its way, retarding its rate of flow, it does not get away quickly, but remains heaped, with an irregularly convex water table, under ridges (Fig. 22). This heaped water flowing out gradually into rivers—the water table meanwhile slowly sinking—during a dry period maintains the flow of the rivers.

Rivers

Not all the water with which rivers are thus fed reaches the sea. Evaporation goes on from the free surface, and this loss may lead to a serious shrinkage in volume—serious, that is to say, in that it will impair a river's ability to perform the tasks of transportation and erosion we are expecting of it—in arid regions where rivers receive no tributaries, as in the case, for example, of the Nile flowing through Egypt. Rivers lose volume also owing to soakage from their beds into alluvium, especially in deserts but wherever the water table is below the floor of the river channel. Many rivers in arid climates dwindle, therefore, to mere threads or chains of

water holes, and finally disappear altogether, as in the interior of Australia. Other rivers debouch into lakes that do not overflow, as inflow is balanced by evaporation from the lake surface—the Jordan, for example, flowing into the Dead Sea. Under normal humid climatic conditions, however, rivers flow to the sea; lakes into and out of which rivers may flow can be regarded as locally expanded portions of river courses; and rivers, as they receive tributaries and are fed by ground-water seepage, increase progressively in volume of flow from source to sea.

Transportation

All flowing streams take part in the task of transportation of waste to lower levels and generally in a seaward direction. In addition, many rivers are assisting in the general lowering of the land surface by actively abrading the bedrock. Others have, at least temporarily, suspended this activity, and are depositing a portion of their load, while continuing in most cases to transport another portion. The deposited material builds landforms, and so such rivers are doing their part in shaping the landscape.

Mud, owing to the extremely slow rate of sinking of its fine particles and flakes, is always carried in true suspension. Sand grains and pebbles, which sink more rapidly, make their way downstream in a series of leaps. There is some turbulence in every flowing stream, and upward currents lift the grains and fragments. When they sink after every such lift, they are farther downstream. Transportation of sand and gravel in this manner was termed "flotation" by Powell,[5] but more recently Gilbert[2] has described it as "saltation". The greater the velocity of flow, in general, the greater the turbulence, and so the larger the pebbles that can be lifted and carried. The strip in which turbulence is greatest is closely associated with the thread of maximum velocity. Larger pebbles, or cobbles, are rolled along.

Enormous boulders, as large as houses in some mountain streams, which have obviously been moved by the streams in the direction of flow, can never have been surrounded by water so deep that current turbulence in it could lift the boulders. Occasionally, probably during a flood, the gravel on which such a large boulder rests is scoured away, leaving it badly supported. After a time, pressed onward by the current and unsupported in front, it rolls

forward a short distance, and this process is repeated many times, though perhaps at long intervals. In some regions very large boulders are transported long distances by mudflows.

Corrosion and Corrasion

In so far as rivers may enlarge their channels by solution their work is in part chemical (*corrosion*); but such work is hard to gauge. Quite a large part of the load carried down by rivers is, indeed, in solution (in the case of the Mississippi about a quarter of the total load), but most of the dissolved salts in river water are supplied to it already in solution by ground-water seepage, and, though they must be taken into account in estimates of the lowering of the general level of the land, they have their origin in surface weathering, not river corrosion.

River *corrasion*, the mechanical cutting and scouring work of rivers, is largely responsible for the deepening and widening of valleys. The stream that does this work is a stream of water and waste, for rock fragments and coarse sand particles in suspension, of such size as to be able to strike an effective blow, are the tools without which a water stream is inefficient as an agent of corrasion. In addition to the fine solid material carried into streams by rain-wash, coarser fragments of all sizes are derived from talus slopes and landslides and the more general process of soil creep. Rock fragments in a running stream soon become converted into rounded pebbles by mutual abrasion as they are swept downstream. While gravel, sand, and mud are all carried by rivers, gravel-bearing streams carry but little sand. Sand grains and also small rock fragments are crushed between the larger pebbles and cobbles and reduced to mud. Thus sand is nowhere an abundant product of rock abrasion, though it is carried in large quantities by some rivers that do not roll along a load of coarse gravel as well. This is in agreement with the results of experimental grinding of gravel carried out by Marshall,[4] who has, however, applied the results more particularly to the explanation of surf work on beaches, believing that under natural conditions crushing of grains by impact and grinding by abrasion are much more effective on beaches than in rivers.

A river the bed of which is covered by a thick layer of waste in transit expends most of its corrasive energy in grinding the waste,

but also scours and abrades outcrops of bedrock where these are exposed on its banks. It is thus able to widen its channel by *lateral corrasion*. *Vertical corrasion* is possible only where the layer of waste in transit on the floor of a river channel is thin and discontinuous. Exposed bedrock is in such a case abraded, and thus the channel is deepened.

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CHAPTER IV

The Cycle of Erosion; Youth of Rivers

It is possible to picture an ideal series of landscapes such as may be developed successively during the wearing down of a part of the earth's surface by erosion; and examples of actual landscapes may be fitted in to match the deduced stages of such degradation, thus justifying the deduction. The whole series of changing reliefs produced by long-continued progressive erosion following a preliminary uplift of a land surface, whatever the pre-uplift form of the land may have been, is a *cycle of erosion*, "geographical cycle", as Davis,[2] the originator of the cycle scheme, preferred to call it, or *geomorphic cycle*, as it has been more recently named in the writings of Douglas Johnson. The surface upon which eroding agents begin to work at the commencement of a cycle is the *initial* surface, its relief the *initial* relief; while the surface of very faint relief which will, according to Powell's principle[9] as it has been expanded in the cycle theory of Davis, eventually result from the prolonged action of normal erosion on a land surface without interruption by further uplift or other earth movements is called a *peneplain*.[3] Another way of describing a cycle of erosion, now abandoned, however, as less useful, is in terms of time—the "cycle" being the period required for the development of a succession of changing landscapes from initial form to peneplain, though it is well recognised that the length of such a period in absolute units must vary within very wide limits.

A truly vast lapse of time, undoubtedly many millions of years (see Chapter XVI), without relative movement of the levels of sea and land is necessary in order that a high land surface underlain by rocks that are resistant to erosion may be worn down to a peneplain, and if we were to form an opinion of the instability of the earth's crust based on the abundant evidence of recent movement in disturbed regions like California, Japan, and New Zealand, the conclusion would be inevitable that a cycle of erosion can

never reach an advanced stage. The evidence afforded by stratigraphical geology, as well as the reasoned interpretation of present-day landscape forms, is, however, sufficiently strong to convince us that cycles of erosion have proceeded far enough in bygone times to produce very extensive peneplains.

Initial Upheaval

A cycle is introduced by uplift, or by its equivalent the withdrawal of the sea to a lower level. It simplifies the elementary study of landscape forms to assume that such uplift or emergence takes place rapidly. It is not to be regarded as ever sudden (catastrophic); but it is possible for it to take place so rapidly that the amount of erosion that goes on during a movement is negligible as compared with that which follows its completion.

Geological evidence indicates that there are very slow as well as relatively rapid earth movements. It seems safe to assert that the results produced by erosion will ultimately be very much the same whether the erosion accompanies and follows a slow or a rapid uplift, provided that sufficient time is available after the movement to allow a cycle to run its course; but such an assertion must be qualified by a free admission that the type of landscape forms developed during certain early stages of the cycle may be controlled very largely by the rate of uplift. Consideration, for example, of the effects associated with very slow uplift introduces the possibility of the land wasting away as rapidly, or nearly as rapidly, as it rises. Similar results are, indeed, to be looked for with even relatively rapid uplift where the materials of the land are very weakly resistant to erosion. Special study of such cases leads some workers to undervalue the cycle scheme of Davis as a basis of description of landscapes and of a descriptive terminology for their features. One may, however, follow Davis in regarding special cases of this kind as more or less exceptional. All such require explanation, but it is possible to fit their explanations into the framework of the cycle scheme.

For the present the postulate of rapid uplift may be adhered to, or this may be assumed to be the general case to be first investigated, exceptions being reserved for discussion later—that is to say, the effects of such erosion as accompanies uplift may be minimised, and even, in an elementary statement, disregarded. There is thus

provided a simplified condition, or case, for elementary or preliminary study, a case which, however, is not hypothetical only, but is rather common in nature, as is indicated by the frequent occurrence of landscape features that agree with its deduced forms.

Initial Surface Form

The initial surface thus uplifted may have previously been a land surface, or it may have emerged from the sea. It may have been formerly flat or may have had any known kind of relief. Further, the relief after rapid uplift may be the former relief unmodified except by incipient erosion, or the pre-existing relief may have been altered by inequality of uplift, former flatness being perhaps replaced by newly developed corrugations.

The uplifted mass may consist of rocks of any kind, and the arrangement of these may be according to any kind of geological structure. It may be, for example, composed entirely of practically homogeneous massive rock—a granite batholith or extensive outcropping of schist of uniform character; or, on the other hand, stratified rocks may prevail, with alternating strata weak and resistant to erosion; and the stratified formations may be horizontally bedded, homoclinally tilted, folded, overthrust, or faulted.

The amount of uplift (relative to sea-level) may be uniform throughout the area, as would be the case if a cycle were initiated by sinking of ocean-level; or, on the other hand, uplift may be uneven.

The possible initial forms on which erosion may begin its work of developing *sequential* forms are thus almost infinitely variable, and it is, therefore, not surprising that the sequential forms in nature also present great variety. Allowance being made, however, for initial differences of form, material, and structure, features of certain kinds are characteristic of landscapes in various stages of the cycle of erosion, so that stages thus recognisable become of great systematic value in the classification and description of landforms.

As a theoretically simple case with which to introduce the study of the cycle of erosion, a previously flat or almost flat surface may be assumed to be upraised to become the initial form, and cases in which moderate or strong relief is inherited from a former cycle may be reserved for later study (Chapter XVIII). The nearly flat surface selected for the initial form may be a *plain of deposition*

built of material deposited in flat layers either of marine sediments or of gravel or finer alluvium spread by rivers over lowlands; or, alternatively, it may be a peneplain that has been developed by protracted erosion of the land surface in an earlier cycle. The abundance of sedimentary rocks of marine origin now forming land shows that the erosional history of most land areas began with emergence of a sea floor. In nearly all cases uplift has been renewed from time to time in such regions, and so present-day landforms on them are rarely referable to the cycle initiated by the first

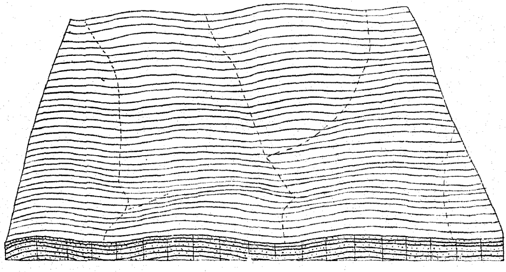


Fig. 23. Diagram of an initial surface and consequent drainage lines in an ideal first cycle, showing conformity of the surface with beds underlying it. (From *Geomorphology,* also by the author.)

emergence. Clearly, however, there must have been such a "first" cycle, and deductions concerning the probable forms of the landscape of the first cycle are helpful in the explanation of many features of the landscape of the present-day or *n*th cycle.

In order to simplify the case still further, uplift of the formerly flat surface may be assumed to be slightly irregular. This is, of course, a gratuitous assumption, but is merely a selection of a common enough variety of case. The uplifted surface is now diversified by broad inequalities of quite small relief and very gentle slopes. The arrangement of these may be quite haphazard (Fig. 23). If the new land has emerged from the sea, however, as an island of broadly domed form, its marginal parts at least will have definite radial slopes, and if a strip of newly emergent sea floor

borders a former land as a "coastal plain", it may be expected to have a fairly uniform slope in the seaward direction. In general, slopes will be sufficiently steep to give streams formed by the run-off from the new surface a definite direction of flow.

The strata immediately underlying the surface, if it has originated as a plain built of sedimentary layers, will be warped during upheaval to the same extent as the surface, so that the initial surface and beds below it maintain their conformable relationship. The topmost layer of material will generally be uniformly weak and unconsolidated, but some of the buried strata may be quite hard and capable of proving resistant to the erosion of the future. ("Weak" and "resistant" are to be understood in the sense of "easily eroded" and "resistant to erosion".) Among the resistant strata are, more especially, layers of calcareous organic debris that are very soon cemented into limestones, but layers of sand may become indurated also, forming sandstones. There will be present also at some depth, great or small, a basement of more ancient rocks beneath the recent deposits, which rest on their worn surface as a floor. These basement rocks, which are relatively very hard and resistant in most cases, and which may have a complex, perhaps intensely deformed, structure, will sooner or later be exposed over parts at least of the surface if erosion proceeds to sufficient depth.

Consequent Rivers

When rain falls and water runs off as streams from an initial surface, the streams are guided by any initial hollows or wrinkles that may be present (Fig. 23), and follow the initial slopes. Such streams are *consequent* (Powell),[9] since they are guided by, or consequent upon, ready-made slopes and corrugations. The valleys which these streams soon cut with the help of the waste they pick up are *consequent valleys*, while the divides, or water partings, between these are *consequent divides*, for their positions are to an equal extent consequent on the initial form of the surface. Complete river systems and valley systems all of consequent origin, each consisting of a main with perhaps many tributaries, may thus come into existence.

In a "first" cycle strata below the surface will be inclined in the same direction as the surface, and consequent streams will flow in the direction of the dip. The practice of calling every stream that

follows the direction of dip consequent has nothing to recommend it, however, and has been condemned by Baulig.[1] Streams that flow in the direction of the dip of the strata they cross may, if it is necessary to indicate this fact, be referred to as "dip" streams[11] or "cataclinal",[9] while those flowing in the reverse direction are "anti-dip"[11] or "anaclinal"[9] streams.

The stage of the cycle entered on when the *infantile* streams that originate on the initial surface begin to incise valleys below it is *youth*. (Later stages in the life-histories of rivers and their valleys are *maturity* and *old age*.) The characteristic features of youth (and also of maturity) in rivers and their valleys on the one hand and in the landscape, or land surface as a whole, on the other are usually treated separately.

Young Valleys

Young valleys may be considered first. Their characteristic sequential features result, in the main, from a general steepness of initial gradients and, where uneven uplift may be assumed, variation of initial gradients from point to point. Steepness of gradients leads to concentration of the erosive activity of young streams on downward cutting (*vertical corrasion*), while changes of gradient cause variation in the intensity and rapidity of vertical corrasion along the course of the stream, causing the cut channel, or true (sequential) valley, to be of irregular depth in the stage of early youth. This is in accordance with Gilbert's principle, "erosion is most rapid where the slope is steepest".[6]

Initial gradients along consequent stream courses may be in some parts uphill, or reversed as regards the direction of flow, in places where the streams flow into and through hollows originating as dimples during uplift or inherited from a former relief (perhaps a legacy of former glacial erosion). All such hollows must become consequent lakes in the new cycle (Chapter V).

Vertical and Lateral Corrasion

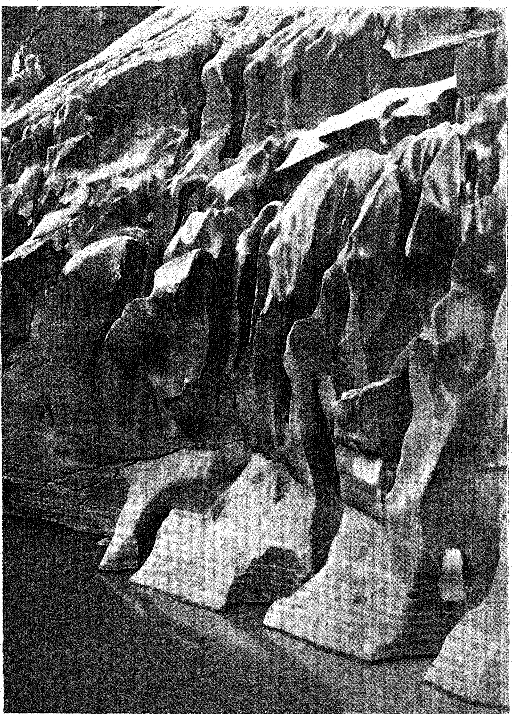
Vertical corrasion, leading to deepening of consequent valleys, goes on in such parts of the stream courses as now have steep gradients and contain streams having, therefore, such rapidity of flow that they are capable of transporting a greater quantity of waste than is supplied to them and they have picked up for them-

selves. In the channels of such streams detritus does not accumulate; on the contrary, the bedrock floor of the channel is exposed and rapidly worn down by the train of rock fragments dragged over it by the current.

Where the supply of waste is limited but includes a proportion of boulders or large cobbles, much of the deepening that goes on where hard bedrock is exposed in the stream bed is due to the excavation of *potholes*—round vertical shafts, 2 or 3 feet across and with a depth sometimes greater than their diameter—which result where boulders or cobbles are whirled around for a long time by eddies. As the first boulders are worn away in the boring process, others take their place, and so some very well rounded stones, generally worn to small dimensions, are found in each pothole. The process of valley deepening by excavation of confluent potholes may be compared with the first roughing out of the interior of his dugout canoe by a modern savage equipped with an auger.

On the rock surfaces of the side walls of gorges remarkable patterns of vertical fluting are sometimes found which are the results of confluence and mutual intersection of innumerable potholes formed in the process of vertical corrasion[8] (Fig. 24).

As a result of the concentration of erosive activity on downward cutting, the young valleys that the streams are now excavating in this early stage of the river are steep-walled—mere trenches or saw-cuts in the uplifted surface—and narrow-floored, being filled from wall to wall by the streams in them except at times of very low water. Where stream corrasion alone is responsible for the formation of a young valley, it is cut as a parallel-walled trench of the same width from top to bottom (Fig. 28). The trench can be vertical only where the stream that is cutting it is quite straight. Where there is any accidental curvature in the consequent course, the momentum of the stream carries the thread of fastest current against the outer, concave bank, so as to corrade and undercut it, and the stream is thus able to move over in that direction as it cuts laterally. This is *lateral corrasion*. Combined with vertical corrasion, which is going on at the same time, it causes the parallel-walled trench due to stream corrasion unassisted by any other processes of valley formation to be cut down diagonally, so as to have one overhanging wall, which leans one way or the other according to the direction of stream curvature controlling lateral corrasion.



E. T. Schenk, U.S. National Park Service, photo

Fig. 24. Fluting by confluence of potholes on the rock wall of a gorge deepened by vertical corrasion, Grand Canyon of the Colorado River.

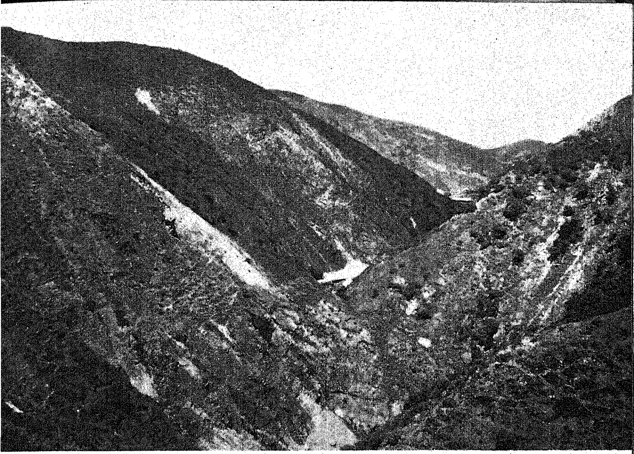


Fig. 25. V-shaped young valley of the Ngahauranga, Wellington, New Zealand.

The development of such narrow, trench-like valleys is possible in actual landscapes only where streams are cutting down very rapidly through exceptionally tough, unweathered rock which is free from joint crevices. Examples are found, however, in the Gorner and Aar gorges in Switzerland—well known to tourists—and in trenches cut by various streams through the Amuri limestone formation of New Zealand. Such gorges are, indeed, commonest in limestone, for, though this rock may be shattered during deformation by earth movements, its fractures are commonly healed again by calcite deposits in veins that fill all the joint crevices. (When selecting examples of young valleys it is impossible to confine attention to "first-cycle" features. Most of the known illustrative examples of geomorphic forms that simulate those of a "first" cycle are of necessity taken from districts that have been uplifted more than once.)

Parallel-walled canyons are really rare landscape features, because few rocks will stand for long as vertical or overhanging cliffs. Most young valleys have been opened out to a more or less broad V shape as a result of the occurrence of rock falls and general down-slope transference of badly supported material from the sides (Fig. 25). Rock debris slips down progressively as the gorge is

deepened, and is carried away by the stream. The quantity thus removed is very much greater than that actually excavated by vertical corrasion in the strict sense (Fig. 26); but it is the deepening of the channel by vertical corrasion that makes possible the development of the V-shaped young valley.

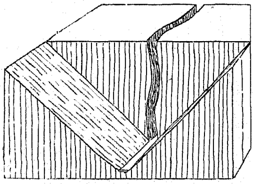


Fig. 26. Diagram comparing the volume of material actually excavated by a downcutting stream (rear block) with that of the material removed when downcutting is accompanied by widening of the valley to a V shape (front block). (From *Geomorphology*, also by the author.)

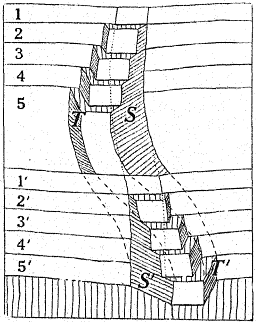


Fig. 27. Increasing curvature of a valley due to lateral corrasion accompanying downward valley cutting. Strips 1, 1′ show portions of the initial, slightly curved course; while strips 2-5 and 2′-5′ show progressive increase of curvature as the valley is deepened. (From *Geomorphology*, also by the author.)

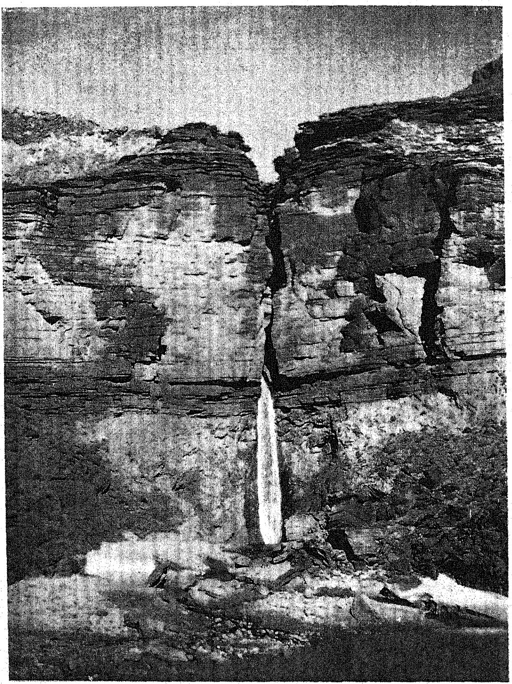
Undercut and Slip-off Slopes

Only in straight reaches is the V form of a young-valley profile symmetrical. More commonly some accidental initial curvature has been increased by lateral corrasion during excavation until the valley has become somewhat winding, so that the river takes its course along a narrow valley floor (of river width only) between interlocking spurs of the upland on either hand. Its V-shaped cross-profile is now asymmetrical (Fig. 27, strips 5 and 5′), having steeper side slopes (T, T') in the coves, or amphitheatres, against which the stream has cut (*undercut slopes*) than on the tapering spurs running down to the convex banks, which are said to have *slip-off slopes* (S, S') because of their mode of development. Small rivers may even wind in S-shaped curves developed by lateral corrasion during valley-cutting, and undercut slopes may approach each other to the point of intersection (Fig. 140). These are "incised meanders" of a kind; but not all such forms are features of a first cycle (Chapter XVIII).

Discordant Junctions

In a first cycle the only tributaries as yet in existence in early youth are, like the main rivers, consequent, occupying subsidiary wrinkles of the surface or flowing down the side slopes of the major hollows or furrows. Where initial slopes are rather steep, these *secondary consequents* may be numerous and closely spaced, but where initial slopes are gentle, few streams may be formed, at any rate where the surface material is open-textured, for precipitation sinks into the nearly level ground, to become ground water and be drained off by the main streams, which are cutting trenches.

While consequent tributaries are young they commonly fail to obey Playfair's law of accordant junctions, as they do not succeed in deepening their valleys as rapidly as main streams, with which they make junctions that remain *discordant*, or "hanging". Discordant tributary junctions are frequently met with in young stream-cut valley systems in later as well as first cycles. They are recognised features at the junctions of side streams with the Colorado River in the Grand Canyon of Arizona[8] (Fig. 28), and such discordance is common, for example, in the Wanganui River system, in New Zealand. In the more widely opened valleys of the Rangitikei and Awatere Rivers also, all small tributaries make discordant



John H. Maxson, photo

Fig. 28. Vertical-walled trench of Deer Creek and discordant junction with the Colorado River in the Grand Canyon.

junctions, but in these cases the initial forms at the beginning of the present cycle were flat-floored open valleys of an earlier land surface, and the main streams have cut for themselves in the new cycle deep, steep-sided trenches (Figs. 29*B*, 158). In their rate of down-cutting they have far outstripped their small tributaries, and so these now cascade from mere notches high on the walls of the main trenches.

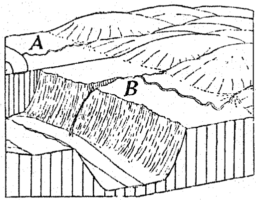


Fig. 29. Development of a discordant junction after initiation of a new cycle. The rear block shows a former condition, in which junctions were accordant, obeying Playfair's law. (From *Geomorphology*, also by the author.)

In the case of those numerous valleys where the initial surface on which water streams begin to flow is one that inherits relief developed by glaciers which were active in the recent Glacial Period, strongly discordant tributary junctions (glacial hanging valleys) are usually present, and, so recent has been the climatic change, the streams descending from these are still infantile in resistant rocks, and plunge as falls from the lips of the hanging valleys.

Infantile Valley Forms

When valleys are of V shape, their top widths (in homogeneous materials, in which uniform side slopes may be expected) must depend on their depths. Thus a young trench cut to varying depths in different parts because of a variable initial gradient will exhibit also variety of width (Fig. 30).

Another effect of initial accidental changes in gradient from point to point must be the occurrence of rapids, and perhaps falls, along the courses of many infant consequent streams. On a first-cycle surface, however, and on any other that is in a similar way

underlain by easily eroded materials, such infantile inequalities of gradient will be smoothed out as young valleys are rapidly deepened. They are transient features, indeed, that will be obliterated by the infantile erosion that accompanies even rapid uplift. Where, on the other hand, an uplifted mass consists of resistant rocks and the initial surface is accidented by fault scarps, falls and rapids due to initial surface inequalities last longer and are to be found in some young landscapes (Chapter XXI).

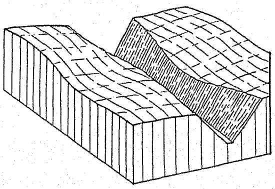


Fig. 30. Variation of width with depth in a young valley.

Falls and Rapids

Other falls and rapids, of a kind that may make their appearance in a "first" cycle, are developed when down-cutting young streams discover rocks of unequal hardness. (Strictly such features, being developed by erosion controlled by rock structure, are "subsequent" (Chapter VII), though occurring in the course of a river that may be itself consequent.) These are generally much longer-lived than any consequent upon initial inequalities of the surface are likely to be. Some rocks, such as shales, mudstones, volcanic "ashes", unindurated sediments generally, and much-jointed or crushed and shattered rocks in fault zones, yield very rapidly to corrasion; others, such as fresh igneous rocks, most metamorphic rocks, limestones, quartzites, and little-jointed indurated sediments, are worn down at a very slow rate. If, therefore, a young stream crosses a geological boundary from a resistant to a weak rock, the weak rock downstream has the channel cut more deeply into it than has the resistant rock upstream, and at the boundary an abrupt steepening of the channel gradient is developed. At such a point there will be a fall or rapid, according to the nature of the junction between the two kinds of rock.

Rapids usually develop, rather than falls, where a junction between resistant and weak rock slopes back, is vertical, or overhangs but slightly (Fig. 31). At the steep slope by way of which the stream descends from the resistant rock, after a deep trench has been rapidly incised in the weaker rock downstream, the velocity increases, and so, before the stream has actually left the surface of the resistant rock, it has its capacity for corrasion enormously increased. As a result, the edge of the resistant rock is cut away

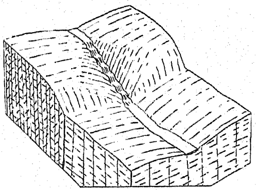


Fig. 31. Development of a rapid at the junction between resistant and weak rocks.
(From *Geomorphology,* also by the author.)

much more rapidly than deepening of the channel in the same rock takes place farther upstream, affording another example of Gilbert's principle "erosion is most rapid where the slope is steepest";[6] and the stream descends by a steep slope with rapids in a notch in the edge of the resistant rock instead of plunging over its edge.

It sometimes happens, however, that such a slope steepens into a fall as it works farther upstream by a continuation of the same process (*headward erosion*); or a fall may develop in the course of a river cutting a young valley in massive homogeneous rocks. The initiation of the process is in most cases obscure, but, once it is started, "plunge-pool back-scour" at the foot of the fall may deepen the valley below more rapidly than the ordinary processes of vertical corrasion above, and the fall works its way upstream, gaining increasing height as it goes. Such falls are *autogenetic.* A great fall in the lower course of the Orange River, in South Africa, is probably of this kind.[4] Similar headward extension and valley-head steepening by plunge-pool erosion in numerous small

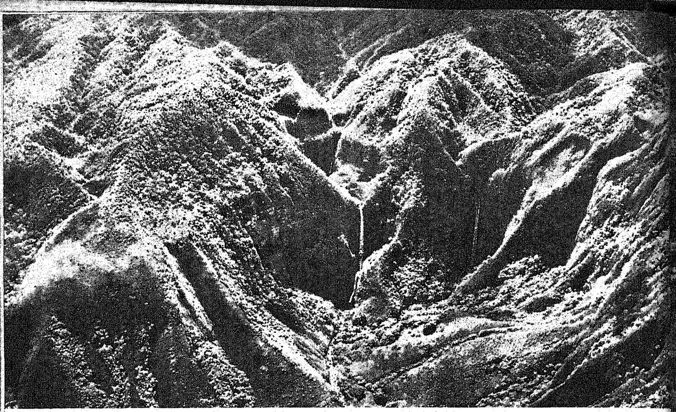


Fig. 32. Halawa Falls, Molokai, Hawaii, illustrating plunge-pool back-scour. *U.S. A.A.F., photo*

intermittent streams go on in deep amphitheatre-headed valleys in basaltic volcanic domes (Fig. 32), notably in the Hawaiian Islands,[10] and certain cataracts in Norway "appear to have gained steepness by this process" (Davis).[4]

Falls, as distinguished from rapids, are developed by vertical corrasion where rivers cross the edges of outcropping strata of resistant rock, and especially where these are horizontal or only gently inclined, and where they overlie weak materials. The resistant beds, *cap rocks* or "fall-makers", may be lava flows or indurated sedimentary strata (Fig. 33). This class of fall, the classic illustration of which is Niagara Falls,[7] is named by von Engeln[5] a "cap-rock fall". Once the fall is established by exposure of the edge of the cap rock in the channel of the river, the underlying weak material is easily and rapidly excavated by the splash and swirl of the water dropping into the plunge pool, which it hollows out beneath the fall (Fig. 34). The edge of the cap rock is thus left overhanging and without adequate support. Blocks of it fall away from time to time, forming a fresh, unworn lip. A fall of this kind retreats rapidly upstream, leaving a steep-sided trench, or canyon, the transverse profile of which contrasts conspicuously with that of the valley above the fall. In the case of the Wairua Fall, in the North Auckland district of New Zealand (Fig. 35), which affords

Fig. 33. Stoneybyres Falls, Lanark, Scotland. *Photo from H.M. Geol. Surv. of Great Britain*

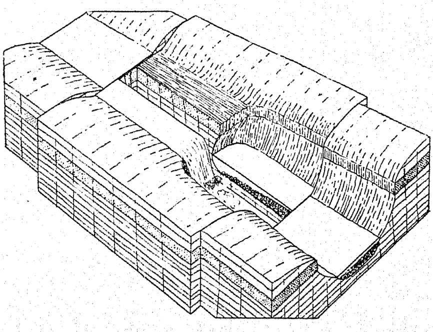


Fig. 34. Dissected block diagram of upstream retreat of a fall in horizontal strata. The middle block is cut in two longitudinally, with the halves separated so that the profile of the edge of the fall may be shown. A canyon is developed below the fall.

(From *Geomorphology,* also by the author.)

Fig. 35. The Wairua Falls, North Auckland, New Zealand.

a very good example of a sharp-edged fall retreating up-valley by plunge-pool erosion and thus developing a steep-sided trench (Fig. 36), the river, instead of crossing the outcrops of sedimentary strata exposed by erosion as is the case in the majority of similar falls, is engaged in cutting a new young valley across a lava flow that has invaded the floor of its former valley. The lava rock itself, though free from joint cracks and resistant to erosion in its surface layer, is weakened below by the presence of tension joints due to shrinkage during cooling, the result being effective undermining of the edge of the superficial strong layer by plunge-pool erosion.

Resistant inclined strata dipping at moderate angles upstream make falls in the same way as do horizontal beds; but in this case the falls can retreat only a short distance, for, as the general surface is worn down, falls give place to short rapids and later disappear. Resistant strata dipping downstream form rapids rather than falls, unless their dip is very steep, in which case cascades are formed. These, like all such features, are short-lived, being worn down to rapids, and later disappearing.

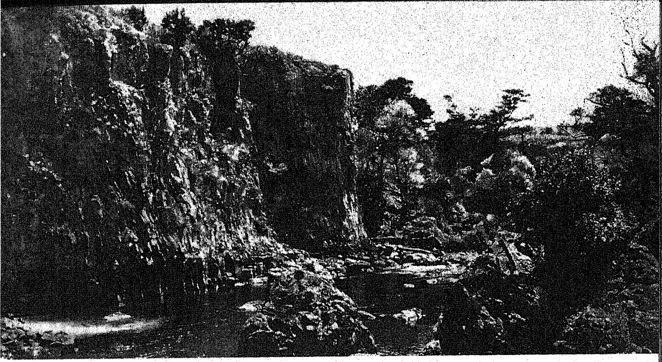


Fig. 36. The canyon below the Wairua Falls. (Compare Figs. 34 and 35.)

Inherited Rivers

In the discussion of the development of valleys of young rivers in this chapter it has been assumed that all the streams are consequent in origin, new-born in the current cycle. Where, however, the initial surface is derived from a land that has been reduced to a peneplain in an antecedent period of erosion, such a surface has already, prior to uplift, its pattern of streams, its river systems; and a proportion of these will survive into, or be inherited by, the landscape of the newly opened cycle. If the preliminary earth movements are rapid and rather strongly differential, so that upheaval is uneven or undulatory, newly born consequents may predominate on the newly uplifted land and play almost as important a part in valley development in the new cycle as they do where the initial form is an upheaved sea floor, but if uplift is more uniform, a greater proportion of the previously flowing streams will be inherited into the new cycle. In particular, such rivers, or parts of rivers, will survive as succeed in deepening their channels appreciably while uplift is in progress, and so entrenching themselves in the landscape, so that they are able, as it were, to defy the efforts of warping and tilting of the surface to deflect them from their courses.

Such survivors will be either the larger and more vigorous rivers or such parts of rivers as flow in the direction in which slopes are steepened. All rivers inherited from an anterior cycle might be

placed in the category of "antecedent" rivers by somewhat extending the definition of that class (Chapter XI). "If, however, the technical term 'antecedent' were thus extended, it would embrace nearly all drainage systems" (WOOLDRIDGE and MORGAN).[11] When it is necessary to insist on the fact that rivers have persisted from a former cycle after nearly uniform uplift has introduced another, they are best described as "inherited". Although a different meaning for this term has been suggested—as a synonym for "superposed"—it has not come into use (and is not required) in that sense. Certain inherited rivers, but by no means all of them, resemble in some respects those classed as superposed (Chapter VI) and have been included by some authors in that category.

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CHAPTER V

Lakes as Young Consequent Features

LAKES WILL BE PRESENT AS CONSEQUENT FEATURES IN THE INFANTILE stage on any surface dimpled by rapid irregular uplift, and the larger and deeper of these may have a long life. Among such are relic seas, like the Aral and Caspian Seas, which occupy the larger dimples of an extensively uplifted ocean floor. Lakes in general. however, are short-lived, and those formed at the initiation of "first" cycles have in most cases long since disappeared. This is true especially of lakes that originate high above sea-level.

LAKES ARE EPHEMERAL

In the steeper parts of the courses of the consequent rivers formed by the overflow from dimple lakes on an infantile uplifted surface, deep trenches will soon be cut (*egf*, Fig. 37), and the heads

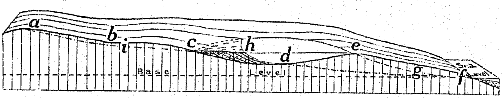


Fig. 37. Draining and filling of a lake on an infantile surface. Initial profile along a consequent stream, *abcdef*; lake, *ce*; later profile, *aichdgf*.
(From *Geomorphology*, also by the author.)

of these will develop farther back (as from *e* to *d*) if the gradients are steep enough. Thus the outlets of lakes are cut down as notches, and the lakes are gradually lowered and drained off. At the same time corrasion will be in progress in all the headwater streams (such as *abc*) that supply a lake with water. These streams. therefore, carry abundant waste, and all the coarser and the bulk also of the finer waste is dropped in the lake. (In Fig. 37 the profile *chd* represents the lake as partly filled with waste before the outlet is cut down.) Much waste being thus deposited in lakes, and even built up above lake-level by inflowing streams, they are rapidly reduced in size. That lakes act as traps for sediment is made obvious

by comparison of inflowing and outflowing river waters. The crystal-clear waters of the Rhone as it leaves the Lake of Geneva and of the Waikato as it leaves Lake Taupo afford examples.

Lakes, whatever their origin and whatever their size, must eventually share the same fate. Low-lying lakes are doomed to disappear from the landscape by filling alone, but in the case of many lakes only partial filling takes place and lowering of the outlet finally disposes of the lake.

Lakes Resulting from Surface Warping

Consequent lakes due to warping of previously eroded land-surfaces are obviously possible, but not many such are recognisable

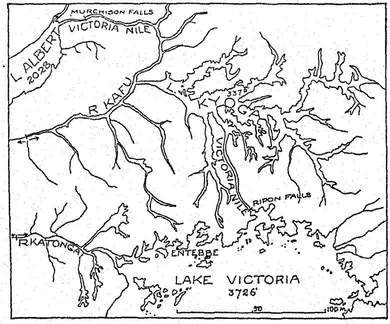


Fig. 38. Lakes of the Upper Nile. (After Davis.)
(From *Geomorphology*, also by the author.)

in existing landscapes, some supposed examples finding a more credible explanation as due to differential vertical corrasion by glaciers. In equatorial Africa, however, lakes have been formed by recent warping of a land surface at the headwaters of the Nile[3] (Fig. 38). Such lakes have intricate embayed outlines, as a result of the relief of the surface that is flooded, thus contrasting with the theoretical simple outline (Fig. 37) of a lake on a dimpled uplifted plain.

The headwater area of a region drained by the Kafu and Katonga rivers has been slightly down-warped, so that their valleys now slope eastward instead of westward as formerly. The branching Kafu headwaters have thus been transformed into the branching Lake Kyoga, 150 miles in length. The Katonga headwaters are more submerged in the broad Lake Victoria, of similar measure in diameter. Parts of both rivers now flow backwards into their lakes. Lake Victoria is the chief source of the Nile, which flows northward from it into Kyoga Lake by one of its branches and out by another. The little eroded Ripon Falls, next north of Lake Victoria, and the extremely narrow gorge below Murchison Falls, north-west of Lake Kyoga, testify to the recency of the time when the lakes were formed and the present course of the Nile was assumed. (Davis.)[3]

Faulting

Instead of being warped at the introduction of a new cycle of erosion, a surface may be broken by great faults, so as to consist thereafter of irregularly heaved blocks, and where such deformation proceeds sufficiently rapidly lakes will occupy undrained re-entrants

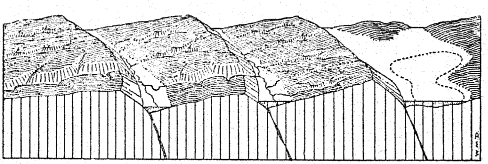


Fig. 39. Great fault blocks of the northern Sierra Nevada, California, with the plain of Honey Lake on the east. (After Davis.)

of the surface (Fig. 39). Classic examples of young lakes on the lowest parts of tilted fault blocks occur in southern Oregon and the adjoining part of California, and large-scale examples of lakes of fault-block origin are Tanganyika and Baikal. Deformation by faulting has probably taken place sufficiently slowly in many block-faulted regions, however, where climatic conditions have been humid, to allow rivers to maintain courses by cutting gorges across block mountains as they arose, and across the intermont troughs or basins also by filling these with deposited waste instead of allowing

them to become lakes at any stage of the uplifting and deforming series of earth movements. "In all cases any lakes that were thus formed occupy merely such parts of the basins as are not otherwise filled" (DAVIS).[3] Lakes, some large, some small, may occur, therefore, on the floors of intermont basins, marking incidents where earth movements have locally gained in the race against erosion and deposition (Fig. 40). The lake Issik-kul, in Turkestan (100 miles long and 30 to 40 miles wide), is situated in a trough of this kind between parallel scarps bounding fault-block mountains that overlook it on the north and south sides. This lake, which is in a dry region, is augmented by inflow through a distributary from the River Chu, but has no outlet and has become somewhat salt.[2]

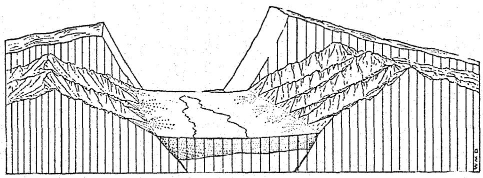


Fig. 40. An intermont trough between block mountains. In the foreground block the trough is partly filled with alluvial detritus with a shallow lake on its surface. (After Davis.)

In arid regions, where tectonic intermont basins are not drained by outflowing streams, the lowest parts of the surfaces of their alluvial filling (Fig. 40)—washed in by sheetfloods and ephemeral streams from the surrounding mountains—are partly covered by shallow lakes that shrink to small dimensions or dry up altogether between the infrequent rains, owing to excess of evaporation over precipitation in the region. Ephemeral lakes of this kind are *playa* lakes, and the plains of saline silt left bare when they dry up are *playas*, or, if kept wet by seepage of ground water, *salinas*. Examples of larger and permanent salt lakes in the deepest parts (remaining unfilled with detritus) of intermont basins in arid regions are the Dead Sea and the Great Salt Lake of Utah. Salt lakes, of course, do not overflow, and their levels, and more especially their areas, are maintained more or less constant by the balance between

evaporation and precipitation in the regions in which they occur. Many of them, including the two cited as examples, have been in the recent past, in an epoch of less intense evaporation, very much larger than they now are, and "Lake Bonneville", which existed in the Glacial Period as an inland sea nearly 20,000 square miles in extent, covering the site of the Great Salt Lake and a great part of the surrounding region, had for a short time an overflow outlet.[4]

Consequent Lakes

Initial hollows in which water collects to form lakes, instead of being due to accidents of uplift or deformation, may be inherited from an earlier land relief, or may even be pre-existing shallow dimples on an emerging sea floor, such as are present on the recently emerged and lowlying coastal plain of Florida.

Glacial Lakes

Countless hollows that have become lakes, both large and small, are present as an inheritance from the Glacial Period in those regions which, like Canada and Finland, were overspread by continental glaciers and scoured unevenly by them down to fresh, unweathered bedrock over large areas of surface just before the present, or post-glacial, cycle of normal erosion was ushered in in such regions by the melting of the ice.

The great North American lakes, from those of the St Lawrence system north-westward 2000 miles toward the Arctic Ocean, are all associated with the scouring action of the vast ice-sheets which covered north-eastern North America in the Glacial Period, although it should not be asserted that they are wholly due to the excavation of their basins by ice action. Lake-basin production there may have been aided by warping of the earth's crust and by morainic obstruction of preglacial river courses. (Davis.)[3]

Among glaciated mountains also the current cycle of normal erosion, still in its infancy, has had as its initial forms the features left over from the foregoing cycle of glacial erosion. Many small rock-rimmed lakes are present in glacial cirques in all such regions, and there are generally also numerous lakes and tarns in ice-scoured hollows on uplands, as well as strung out in line along the floors of glaciated valleys, and others are ponded by dams of glacial rock

debris. These small lakes are countless. Larger lakes occupy more deeply gouged-out rock-rimmed basins, especially in the piedmonts or fringes of groups of glaciated mountains. Without making any attempt here to discuss and evaluate alternative theories of tectonic origin that have been proposed in explanation of such piedmont lakes, one may follow Wallace[9] in his rejection of them and complete acceptance of an explanation of the lakes as the result of differential deepening by glacial corrasion under the thickest parts of the deep ice of great valley glaciers.

The importance of glaciation in the production of lakes may be judged by the number and size of such lakes in various parts of the world. For example, Okanogan, Arrow, Slocan, and Kootenay, in British Columbia, 60, 95, 23, and 68 miles in length, and the 65-mile Lake Chelan in Washington, all in valleys of the Columbia River system, occupy basins of glacial excavation. The same is true of the piedmont lakes of the Alps, including Annecy, Geneva, Thun-Brienz, Lucerne, Zurich, Constance, Ammer, Würm, and Chiem on the north, and Maggiore, Lugano, Como, Iseo, and Garda on the south. Some of these lakes are over 1000 feet deep. (Davis.)

To the foregoing might be added a list of lakes in every glaciated mountain region, the English lakes (Fig. 41), for example; while the New Zealand list includes Manapouri, Wakatipu, Wanaka, Hawea, Ohau, Pukaki, and Tekapo.

Piedmont lakes are fringed at their lower ends by terminal moraines, in some cases very extensive, and morainic dams in some cases impound water in large areas outside the mountain fronts, so that the lakes are thereby much enlarged, as well as having their levels held up considerably above the lips or rims of the actual rock basins within the valleys. Notable examples are Lakes Constance and Garda, and some of the New Zealand lakes.

The deeper and larger of the lakes of glacial origin will survive for aeons, as man counts time, but rivers are busily at work pouring waste into them, and, geologically speaking, their days are numbered. Many quite large lakes have already disappeared from the landscape in the few thousand years that have elapsed since the melting of the glaciers, and the great deltas already built by in-flowing rivers in many lakes—for example, those of the Rhone and Rhine in Lakes Geneva and Constance—testify to the rapidity with which even large lakes like these are being filled.

Fig. 41. The English lake Ullswater, of glacial origin.

Classification of Lakes

Lakes that are not due in simple fashion to the existence of undrained hollows in the initial surface may also be classed as young consequent features of the landscape, or they originate as a result of local modifications of pre-existing features—most often the blocking of river valleys. Their causes are accidents interfering with the normal course of events of the cycle in progress, and these locally introduce new young forms, among which are the lakes. A glance at a simple classification of lakes used by Davis[3] will help to make this clear.

Among the classes of lakes recognised *warped-valley lakes, fault-basin lakes,* and *glacial lakes* have already been discussed. In addition to these the list comprises *landslide lakes, volcanic lakes, river-made lakes, artificial reservoirs,* and *lake-like bays and lagoons.* An additional class, "lakes formed by local subsidence", might be added, to include *sag ponds,* mentioned by Davis, which are formed along the lines of active faults, *earthquake lakes* (Hobbs),[5] formed by settlement or readjustment on alluvial plains during earthquakes, *pit lakes* (Hobbs),[5] due to melting of ice blocks buried under fluvio-glacial deposits, forming kettles, and lakes in sinkholes and subsided areas underlain by limestone that is undergoing solution (Fig. 352).

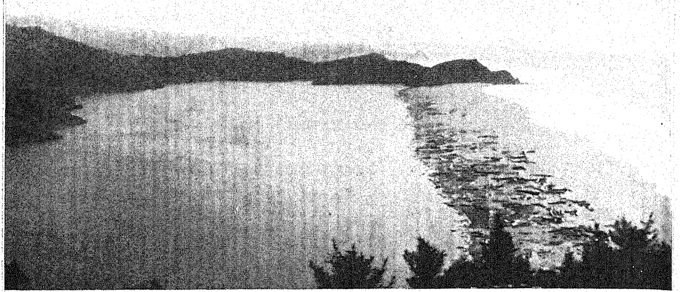


Fig. 42. Freshwater Lagoon, a bay-bar lake near Eureka, California. *Patterson Pictures, photo*

Bay-bar Lakes

Bays enclosed by bay-bars of sand or gravel and so converted into lagoons (Fig. 42), being really shoreline feaures need be no more than mentioned in this book. Onoke Lake (Fig. 43) serves as an example; its companion lake, Wairarapa, is partly "river-made", having become separated from Onoke Lake by the delta of the Ruamahanga River.

River-made Lakes

River-made lakes include a rather varied assortment developed during progressive changes in river meanders (Fig. 151) and features of deposition on the floors of valleys that are being filled with alluvial deposits. Other river-made lakes are those ponded either in tributaries by rapid deposit of waste on the floors of main valleys (Fig. 43), or in main valleys by the upbuilding across them of fans of waste brought in by tributaries. (A better understanding of these can be attained after the principles governing deposition of waste in river valleys have been discussed in Chapter XV.) The cutting off and conversion into a lake of what might be regarded as an arm of the sea at the head of the Gulf of California by the fan-like delta of the Colorado River comes under this head. Actually tectonic sinking of an earth block appears, however, to be the main cause of the origin of the Salton Basin, the great hollow, more than 2000 square miles in extent, which lies north of the Colorado delta, with

much of its floor below sea-level.[1] Owing to aridity of climate, the lake in this deep hollow is now of small dimensions (p. 268).

Landslide and Other Impounded Lakes

Lakes that occupy parts of former valley floors on which they are impounded by landslides (Fig. 9) or by naturally formed dams

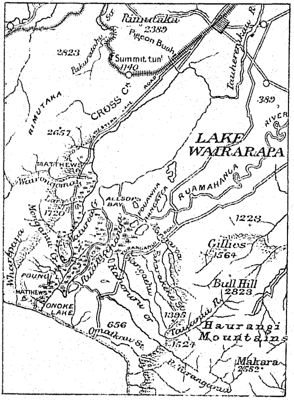


Fig. 43. Wairarapa Lake, New Zealand, has been separated from the bay-bar lake Onoke by growth of the Ruamahanga delta.
(From *Geomorphology,* also by the author.)

of other kinds, such as alluvial fans and volcanic accumulations (Fig. 44), have a good deal in common, resembling also those held up by dams of man's making as artificial reservoirs, or, in the case of the widely spreading Gatun Lake, in Panama, as a route for ships between oceans. Some valleys that have been widely opened out by glacial erosion and afterwards abandoned contain scattered lakes in hollows among large postglacial alluvial fans. These are well exemplified by a group in western Canterbury, New Zealand, in the foothills of the Southern Alps, among which is Lake Lyndon (Fig. 200).

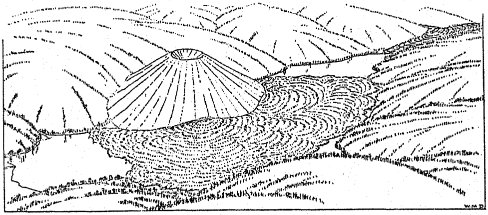


Fig. 44. Lakes impounded in river valleys by lava. (After Davis.) (From *Geomorphology,* also by the author.)

Many lakes impounded in valleys and valley systems have intricate outlines, with embayments extending up tributary valleys, but their details of outline are related in all cases to the nature and stage of relief of the landscape that they partly submerge. An example of a large landslide lake is Waikaremoana (Fig. 45), in New Zealand.[7] In this case a gorge through a ridge of sandstone, the escarpment of which is seen in the illustration, is blocked by an enormous rock slide. A recently formed landslide lake of smaller dimensions—contained in the slump scar—is shown in Fig. 46.

Fig. 45. Waikaremoana, New Zealand, a large lake held up to 2060 feet above sea-level by a rock slide.

Fig. 46. Lake ponded by a large landslide formed at the time of the earthquake of 1855, Mt Bruce, Wairarapa, New Zealand. *M. Ongley, photo*

Lake Nicaragua, in Central America, is held up, at least in part, by a dam consisting of a chain of new volcanoes. New Zealand examples, chosen for purposes of illustration, are Lake Rotoaira (Fig. 47) and Lake Omapere. The resulting diversion of drainage in the case of the latter has taken place across a former main divide,

Fig. 47. Lake Rotoaira, New Zealand, which is impounded (in part) by lava flows from the volcano Tongariro. The promontory is a lava flow.
Professor Douglas Johnson, photo

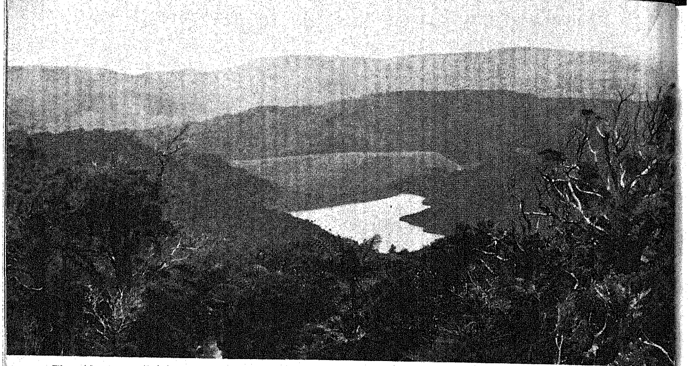


Fig. 48. A small lake in a valley blocked by a wandering dune, near Auckland, New Zealand. *T. L. Lancaster, pho*

affording a small-scale parallel with Lake Nicaragua, the waters of which spill over eastward across a former continental divide into the Caribbean Sea. Ponding of a small lake by a dune of blown sand near Auckland, New Zealand, is shown in Figs. 48 and 49.

Volcanic Lakes

Davis's division "volcanic lakes" includes also those in craters (Figs. 50, 51) and in some of the much enlarged craters termed

Fig. 49. The outlet stream (Waitakere) and a closer view of the dune that holds up the lake shown in Fig. 48. *Professor J. A. Bartrum, phot*

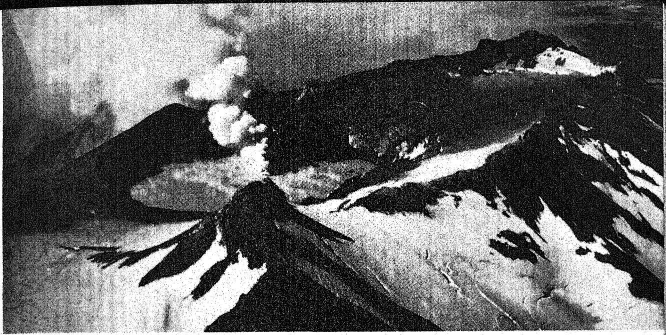


Photo from R.N.Z.A.F.

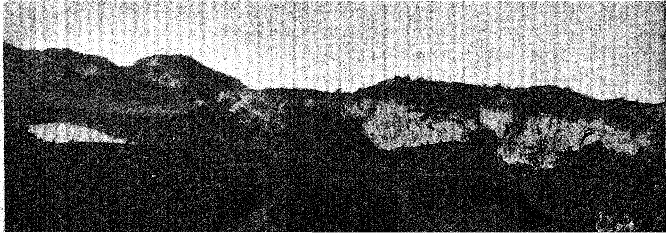
Fig. 50. Crater lake, Ruapehu volcano, New Zealand. Activity of the volcano in 1945 (of which an early stage is shown) resulted later in displacement of the lake by lava.

"calderas". Lake Taupo, the largest lake in New Zealand, has been explained as formed in part by volcanic explosions,[6] though in part also by subsidence along faults, high scarps of which bound it most conspicuously on the western side (Fig. 52).

Lake Floors

Lake floors, together with all the marginal features resulting from delta-building and development of shoreline forms both by erosion and by deposition of waste, become initial surfaces of a special kind when lakes are drained, and on these a cycle of erosion must locally develop through infancy and youth. The silt-covered floors especially demand a brief reference at these stages of erosion.

Fig. 51. Lakelets in the caldera of the Mayor Island extinct volcano, New Zealand.



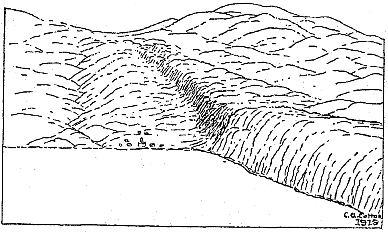


Fig. 52. Fault-scarp of the western shore of Lake Taupo, New Zealand, running inland in a southerly direction.

(From *Geomorphology*, also by the author.)

Fine silt, deposited widely and evenly from the lake waters, if present in sufficient quantity, fills in hollows and levels off the lake floor. Some lake-floor plains are very uniformly level over large areas. Such, for example, is the plain forming the valley of the Red River of the North, in Minnesota, North Dakota, and Manitoba. It is a part of the floor of the vast extinct "Lake Agassiz",[8] which at its largest covered 110,000 square miles, and which was ponded at the end of the last glacial epoch between the northern ice sheet and the gentle northward slope of the surface of North America. The consequent rivers on it are still infantile. This is the case also in the Imperial Valley, the lake-floor bottom of the Salton Basin, in arid Southern California, which, being below sea-level, is not in danger of deep erosion.

Lake floors at higher levels, however, have young valleys incised in them in the same manner as level sea floors uplifted without warping or emergent owing to eustatic sinking of sea-level. A broad "lacustrine coastal plain" fringing the southern shore of Lake Erie, for example, is undergoing dissection as a result of its very recent emergence from beneath the lake waters, and the larger of the consequent streams that cross it have already cut young valleys to a depth of 150 feet below its surface.

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CHAPTER VI

Maturity of Rivers; Superposed Rivers

In the account of the activity of young streams given in Chapter IV, it was assumed that the streams flowed in their infancy at considerable heights above the sea, under which condition their average slopes and velocities would be high and they would cut downward energetically. There is, however, in all cases a sharp downward limit to such active vertical corrasion.

Base-level and Grade

As a stream cuts down so as to approach *base-level*—as defined by Davis,[8] following Powell,[10] the originator of the base-level idea, this is an imaginary extension of sea-level under the land—the rate of deepening rapidly decreases, for the level of the stream, though it approaches base-level, can never quite reach it except where it enters the sea. In order that the water of a river may be able to flow, its surface must have a certain slope down to the mouth, which in the case of rivers flowing into the sea is at base-level (sea-level). Every part of the channel of the stream must, therefore, remain at such a height that there will be a gradient steep enough to carry off the water. The necessary slope is steeper for waste-laden water than it is for clear water.

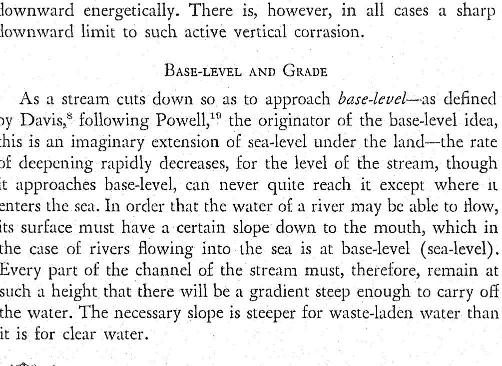

Fig. 53. Longitudinal profile of a graded river, showing the relation of grade to base-level.
(From *Geomorphology,* also by the author.)

The minimum necessary slope varies not only in different streams and at different times, but also in the same stream and at the same time with varying conditions, chief among which is

distance from the mouth. The necessary slope becomes steeper with increasing distance from the mouth, mainly, it is generally believed, because towards the source the volume of the stream is less. "*Ceteris paribus*, declivity bears an inverse ratio to quantity of water" (GILBERT).[10] According to Challinor,[5] however, the concavity of profile exhibited by most rivers is due not so much to downstream increase of volume as to the influence of base-level. In agreement with Bain[1] he deduces that "a stream not working to a base-level has a convex profile." A concave profile controlled by base-level replaces an earlier formed convex profile except very close to the source, where convexity persists, though the "relative insignificance" of this portion of the profile "causes it to be overlooked" (BAIN).[1] Bain's explanation of profile development was accepted by Chamberlin and Salisbury.[6]

A stream that has attained the minimum slope under existing conditions is said to have reached *grade* (Davis),[7, 8] or to be *graded* (Fig. 53). The concave profile of a graded stream approximates to a hyperbolic curve, the so-called *profile of equilibrium*.[3, 18] There are in all cases. however, small departures from the ideal curve, which are due largely to irregularity in the rate of increase of stream volume downstream, an increase that results in part from the junction of tributaries of various sizes at irregular intervals.

A factor that influences the steepness of the graded slope at any particular place and time is the amount of waste being supplied farther upstream. This material has to be transported, and the fact that the profile is graded at any place implies that the supply of waste to the stream by tributaries and in various ways from the valley sides is approximately equal to the amount the stream can carry past that place. If the supply were greater, the surplus would be deposited farther upstream in the river channel, which would thus be steepened, giving the flowing water progressively higher velocity and transporting power until it was able to carry the whole of the waste supplied to it. If, on the other hand, the supply were less than the stream could dispose of, its bed would be swept clear of waste and it would further deepen its channel, reducing the slope and so decreasing its own velocity and transporting capacity. The graded condition thus indicates approximate equilibrium between the amount of waste supplied and the transporting capacity of the stream, and also between the processes of vertical corrasion

and deposition in the channel of the stream. In addition to gradual increase of volume downstream two other requisites are indicated by Baulig[3] for a continuously concave and smoothly curved profile. These are: (*a*) the increase of load of waste must be gradual and must not pass a certain limit; and (*b*) the waste carried must become progressively finer downstream. Where large tributaries enter the main river these conditions are not in all cases fulfilled—for example, where the tributaries Saone and Isère join the Rhone—with the result that there are irregularities and even small convexities in the graded profile of the main river.

It cannot be asserted that there is at any moment perfect balance between load and carrying capacity in a graded river, for conditions are constantly changing. Insistence on equilibrium as a condition of grade may lead, indeed, to subtle disputation. It may be argued that graded streams are not fully loaded, for if they were they would be unable to transport the debris derived from lateral corrasion; but, on the other hand, they are overloaded, for otherwise they would not line their channels and keep them lined with the debris that protects them from further vertical corrasion. So Kesseli[13] expresses a preference for defining the graded condition of a river by reference to its symptoms (smooth gradient, without falls or rapids) without attempting to explain it; but he recognises the control of gradient by volume and load. Like Baulig[3] he thinks of a river as doing most of its work and adjusting its gradient when in flood. "Each flood modifies the gradients of the stream bed according to its specific conditions of volume, rate of increase and decrease of discharge, availability of load, etc." (Kesseli).[13]

Degradation and Aggradation

When, owing to excess of transporting power over waste supply, a stream cuts downward to establish or maintain grade, it is said to *degrade*; and the process is termed *degradation*. When, on the other hand, owing to excess of waste supply over transporting power, a stream deposits in and so builds up its channel to establish or maintain grade it is said to *aggrade*; and the process is *aggradation*. In streams that are not yet nearly graded degradation goes on rapidly, as is shown by the prevalence of narrow, steep-sided valleys among those of young rivers. Once grade is established vertical

corrasion goes on infinitely more slowly, though it does not necessarily cease altogether. Afterwards the slope of the graded profile will be further reduced in steepness, but only with extreme slowness, and possibly with some intermittent reversals of the process, for it can take place (except under changed conditions, for example, of climate) only as the supply of waste falls off owing to gradual reduction of relief in the whole valley system.

MATURITY

Falls, rapids, and lakes (Fig. 37) introduce irregularities into the longitudinal profiles of rivers that traverse them, and so must be smoothed out and disappear before a river is graded. The complete elimination of such features marks the end of the stage of youth in a river, and the establishment of grade marks the passage of the river from youth to *maturity*, the next main stage of the cycle, though rivers in a transitional condition from youth to maturity may sometimes be conveniently referred to as *adolescent.*

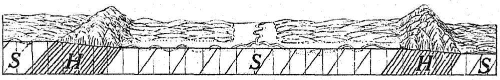

Fig. 54. Graded reaches. The longitudinal valley profile of a transverse stream crossing the outcrops of resistant (*H*) and weak strata (*S*) is shown on the front edge of the block diagram. The river is graded on the weak but not on the resistant rocks.

(From *Geomorphology,* also by the author.)

Most rivers become mature earliest in their lower courses, where their volumes are largest; and generally the mature, graded valleys extend from the lower courses gradually headward. The last statement is true only in a general way, however, for it takes no account of the hardness of, or resistance offered to erosion by, the rocks over which a river flows. A river crossing the outcrops of alternating weak and resistant rocks will very early develop *graded reaches* across the outcrops of weak rocks, while the profile remains for a long time irregular and steep across resistant rocks, where falls and rapids still survive (Figs. 54, 55).

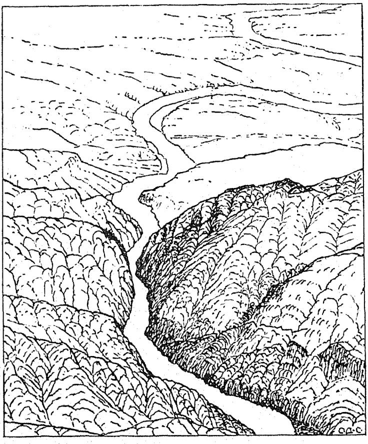

Fig. 55. Looking through the Boulder gorge of the Colorado (site of the Boulder dam) at a graded reach of the river farther upstream. (Drawn from a photograph.)

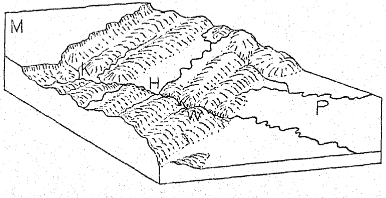

Fig. 56. Graded reaches of the Hunho system above a local base-level in the gorge of the Hunho. "Adjustment to structure" is shown by parallel ridges. M, Mongolian plateau; P, Peking; K, Kalgan; H, Hunho valley system; W, gorge through Western Hills. (After Barbour, redrawn.)

Graded Reaches and Temporary Base-levels

Graded reaches may be high above the *general*, or *permanent*, base-level, which is sea-level, but each is governed by a *local*, or *temporary*, base-level, which is the level of the first outcropping ledge of the next resistant rock downstream. The wearing away of this resistant rock takes place so slowly as to be practically negligible as compared with the rate at which the adjacent weak rock can be degraded. Thus, though a temporary base-level of this kind is always being lowered, grade is maintained meanwhile across the weak rock next upstream. In course of time grade is established across the resistant rocks also, the graded reaches become joined each to the next, and the stream becomes graded and mature for a great part of its length. The conception of local, or temporary, base-levels, like that of the general base-level, was introduced by Powell.[19]

The North China region presents large-scale examples of rivers and river systems graded with respect to temporary base-levels. The rivers descend from the north-west towards the plain of North China and cross the outcrops of resistant strata that form parallel ridges with a north-easterly trend in a belt of folded strata between the margin of the Mongolian plateau and the plain. The temporary base-level in the Western Hills of the Nankou Range thus holds up the Hunho and its tributaries to form a system of graded valleys 1200 feet above the plain (Fig. 56).[2]

Compound Structure

In the ideally simple case of streams eroding flat-lying or only very gently warped strata underlying a newly emerged sea floor, such as that pictured in Fig. 23, an alternation of weak and resistant rock outcrops such as develops local base-levels controlling graded reaches would be unlikely to occur; but where the initial form at the beginning of the current cycle is an ancient land surface, this structural arrangement is not uncommon. It may be present also beneath newly spread sediments on a land that has just emerged from the sea. In such a case, if the superficial layer of sediment is somewhat thin, the edges of weak and resistant strata beneath it may be soon discovered and exposed by streams as they deepen their early consequent valleys. They are afterwards confronted with the more difficult task of deepening their still ungraded valleys in

rocks of diverse structures and generally more resistant to erosion than is the material immediately underlying the initial land surface (Fig. 57). This structure is *compound* in that it comprises beds with two contrasting arrangements, simple above in the *cover*, and complex below in the *undermass*, upon which the cover rests unconformably.

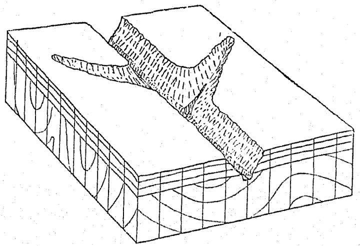

Fig. 57. Young landscape underlain by compound structure. Streams are being superposed on an undermass of folded rocks from a flat-lying cover.

Superposed Consequents

When streams that are consequent on the surface forms and the associated simple structures of a cover, which may have suffered no deformation other than slight tilting or very gentle warping, cut through it and discover an undermass of older rocks with different structure, they become *superposed consequents*. The description "superimposed", used first by Maw[17] and later by Powell[19] was shortened to "superposed" by McGee.[14] Richthofen[20] termed the courses of such rivers "epigenetic". Streams that are other than consequent, if they develop on a thick cover during early stages of a cycle of erosion, may also become superposed (Chapter XI), and their stream patterns may be stencilled on the quite discordant rock structures of an undermass.

A series of stages of superposition is possible, beginning with that in which rivers are still flowing mainly on the cover and have exposed only occasional ledges of an undermass in their channels, and ending with that where they have cut down far into an undermass from which prolonged erosion has entirely removed the cover.

An interesting intermediate stage is that at which only occasional remnants of the basal beds of the cover remain here and there in the landscape on the highest parts of ridges. From such remnants the former widespread extension of the cover may be inferred, and the superposed origin of the valleys demonstrated.

Systems of valleys with definite patterns resulting from superposition and entirely unrelated to the rocks and structures across which they are stencilled are recognised in various regions. Notably such an explanation has been adopted for the rivers of the south of France,[4] and river courses transverse to hard-rock ridges in the

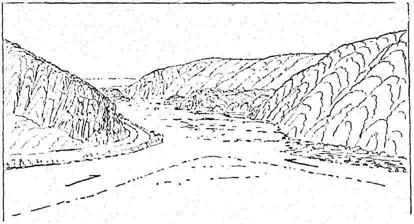

Fig. 58. The Shenandoah (right) unites with the Potomac (left) to pass through the Blue Ridge of Virginia in a superposed consequent water gap. (Drawn from a photograph.)

eastern United States have also been shown to be superposed from a former widespread cover of marine strata on which they had taken consequent courses[12] (Fig. 58). One of the most striking of known examples is the system of radially arranged valleys of the English Lake District, which are believed to be superposed from a dome-shaped uplift of a former cover, with its centre over Helvellyn. Though they are entirely removed from the central area, a ring of the covering strata still surrounds this district[15, 16] (Fig. 59).

The essential characteristic of a superposed river is lack of relation of any kind to the structures of the rocks across which its course has become fixed by vertical incision (Chapter XI). Gilbert[11] and McGee[14] have pointed out that there may be other rivers so placed besides those stencilled on an undermass from a cover. These may merely have got out of adjustment to underlying structures by

wandering uncontrolled on a very well planed-off land surface in an earlier cycle, and such rivers they have included in the "superposed" category.

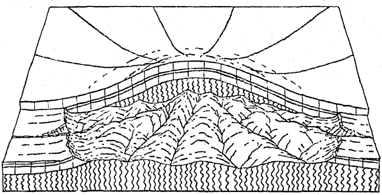

Fig. 59. Development of radially arranged superposed consequent valleys.

Aggradation in Mature Rivers

As suggested on an earlier page in this chapter, the graded profile of a river that has entered on the stage of maturity, and will become more and more fully mature and eventually old, may not be continuously lowered and reduced in steepness throughout these stages, though in the long run such degradation is inevitable. A phase, or phases, of aggradation may temporarily steepen a graded river profile as a whole or the profile of a graded reach. More or less contemporaneously with the grading of river valleys, dissection of the whole upland region is in progress (Chapter VII); a vast number of small new valleys and ravines come into existence in the stage of youth, and thereafter and until the cycle is far advanced the valleys are becoming wider. Thus throughout all this time the proportion of the whole area that is occupied by valley-side slopes steep enough to yield abundant waste is increasing. The waste has to be carried away down the main valleys, and river loads must, therefore, increase during this phase. Later, however, as relief is lowered by the wasting away of ridges and spurs during the progress of the cycle, the slopes will yield progressively less and finer waste. If the discharge of waste from the general surface, and, consequently, the loads of waste carried by the rivers, reach their maxima before the rivers are graded, the gradually diminishing loads during river maturity can and will be disposed of by rivers that flow down

courses of gradually diminishing declivity, which is equivalent to saying that slow degradation will go on uninterruptedly after the graded profile has been first developed.

If, on the other hand, as it seems probable will sometimes be the case, the maximum of waste discharge and river load is not reached until after the rivers have become graded, then a phase of steepening by aggradation may intrude after streams are graded, though this must be followed in later maturity by renewed degradation. Deposits spread on the floors of valleys during the aggradational phase will then be gradually removed again, and weakening of gradients will continue throughout all the latter part of the cycle.[7] An aggradational phase may fail to occur even in this case, however, for run-off of surface water will be facilitated by the development of an elaborate system of tributaries, "and it is possible that the increase of river volume thus brought about from youth to maturity may more or less fully counteract the tendency of increase in river load to cause aggradation".[7]

Other causes of possible temporary aggradational phases can be suggested, and any two or more causes may be in operation simultaneously.[10] As a river after it is graded flows generally in a wider channel than it has hitherto had in youth, when it has been confined to the narrowest limits by downward corrasion, loss of depth in the stream may involve such loss of velocity and transporting power that a steeper gradient will be required to carry the load.

Again, as a river develops increasingly large curves by lateral corrasion, its length increases, with the result that it loses some fall, velocity, and carrying power, the automatic remedy for which loss is aggradation.

Yet another cause of aggradation is loss of river volume by underflow through porous alluvial deposits which the river has laid down. As alluvium is extremely porous, the presence of an alluvial filling in a valley, or even of a gravel veneer on a valley floor, will facilitate underflow, which conceivably may draw off so much water from the river as to reduce its carrying power appreciably, thus causing further alluvium to be spread (aggradation) and perhaps producing a cumulative effect. Taking up an oral suggestion of O. Lehmann, Davis[9] developed this hypothesis as "Lehmann's principle", but later[10] regarded it as unimportant; for, if some aggradation should occur, a "rapid gain of carrying power due to increased velocity"

in the course steepened by aggradation would "soon make up for the slower loss of carrying power due to loss of volume".[10] Baulig[3] has pointed out also that loss of volume due to underflow is no greater during floods than it is when the river is low, whereas it is during floods that rivers grade their profiles, and at such times river volumes are so great that the small loss to underflow is negligible.

In all cases decreasing load in late stages of the cycle—i.e. after uplands have been worn down to small relief—must eventually terminate these aggradational phases, and a river will not only carry away piecemeal the alluvium it has itself deposited in its valley, but will also "return to the long-postponed task of slowly wearing down the rock basement of its first graded course".[10]

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CHAPTER VII

The Landscape in Youth and Maturity

SIMULTANEOUSLY WITH THE RIVER CYCLE, WHICH HAS BEEN OUTLINED in the foregoing chapters, the landscape, or general land surface, also runs through its stages of youth, maturity, and old age. Although parallel, however, the stages of the landscape cycle are never quite co-extensive with those of the river cycle. As different criteria for stages, and especially for the important transition from youth to maturity, must be applied, it is quite possible for a young landscape to be traversed by mature rivers, while, on the other hand, a landscape may reach maturity while its rivers are still young.

THE LANDSCAPE CYCLE: YOUTH AND MATURITY

Essentially the early stages of the landscape cycle involve first the gradual modification and, later, the destruction, or elimination from the landscape, of the initial surface and its replacement by forms of relief developed wholly in the current cycle. When this goal is attained by the erosional processes, the landscape is mature, but as long as parts of the initial, or infantile, form are preserved, it is still young. While this criterion of maturity, devised by Davis, is strictly applicable in landscapes of homogeneous rocks, considerable latitude must be allowed in its application in regions of heterogeneous rocks. Small residuals of an initial form may survive in places where rocks are exceptionally resistant long after the initial surface has been destroyed and the land surface reduced to a level far below it over other and much larger parts of a landscape. In such a case a strict application of the rule would require the landscape as a whole to be classed as young, whereas a great part of it (excluding only the residuals) may be far advanced in, or even have progressed beyond, the stage of maturity. "Parts of the intricately dissected Allegheny Plateau, with no upland remaining, are for sound reasons commonly accepted as the type of a mature plateau"; but another plateau in large part reduced to a peneplain may "yet have scattered monadnocks with summits preserving appreciable

expanses of the original upland" (Johnson).[11] Rigid application of the rule announced above would require the latter to be classed as young; but Johnson[11] prefers to call it old. An alternative method of classifying landscapes as young, mature, and old, advocated by Johnson[11] is based not on survival of any, or of any specified proportion, of the initial form, but on the proportion of the actual mass of material available for removal—i.e. standing above the average level of what will be local base-levels when streams become graded—that has actually been removed, the landscape being mature when from one-third to two-thirds of such mass has been eroded away.

Usually only a beginning has been made when the parallel-walled, or more commonly open V-shaped, valleys of young rivers, such as have already been described, are developed. Though these valleys are entirely the result of erosion in the new cycle, they are narrow, and if widely spaced occupy only a part, perhaps a small proportion, of the total area. Throughout the stage of youth the general outlines of the relief are determined by the form of the initial surface, which is still retained by the *doabs*,[6] or strips on the interfluvial areas. Generally these are broad at first, but later they are nibbled away until they become narrow or discontinuous, and eventually they disappear, marking the passage of the landscape from youth to maturity, according to Davis's rule.

On a newly emerged surface (i.e. in the case of a first cycle), and especially on one without steep gradients due to inequalities of uplift, consequent streams, including tributaries, are generally spaced rather widely and, in early stages of erosion, streams of other kinds have not yet been developed. From the air, therefore, the newly cut young valleys may be scarcely noticeable, and large tracts may appear to retain the initial forms without modification. Plateau regions in which the initial form of the present cycle is an uplifted peneplain of a former cycle may also retain strips little modified by erosion (infantile) on the broad or narrow interfluves between deeply incised valleys. This is the case on the Blue Mountains upland and Southern Tableland of New South Wales (Fig. 60).

The destruction of an upland by the development of valleys cut below its surface is *dissection*. One may also think of the "dissecting" agencies as developing landforms by a process of *sculpture*. As the cycle progresses towards maturity the initial or infantile

Eric Merton, photo

Fig. 60. Youthful dissection of an uplifted peneplain, Southern Tableland, New South Wales, from Shoalhaven Lookover.

surface will be dissected and eventually destroyed, in part by deep development of valleys already present in early youth (consequents, together with those persisting in some cases from an antecedent cycle), and in part by the birth and development of new valleys of various kinds that come into existence in the course of the cycle.

Dissection by Consequent Streams

Consequent valleys alone, without assistance from those of other origin, rapidly dissect some surfaces that have somewhat steep initial declivities, especially when these are underlain by soft materials. On a surface of minutely diversified initial relief, streams, mainly secondary consequents, are numerous and closely spaced, and such of them as run at first down the steeper slopes at once begin the work of dissection. When the closely spaced valleys of these are incised to some depth, the sloping sides of adjacent valleys intersect. The surface is then maturely dissected, for no remnants of the initial form survive on the interfluves. Where the superficial material is unconsolidated fine sediment, such dissection takes place so rapidly that, as compared with the rate at which most erosion proceeds, it may be considered instantaneous. It will, at any rate, be far advanced before the most rapid of initial upheavals

is complete, and so one need not expect to find any strongly warped and uplifted sea floors, for example, in a stage of youth or immature dissection.

On even moderately inclined surfaces, if the ground is not too absorbent, so that there is considerable run-off, large numbers of closely spaced consequent streams are formed. These deepen their valleys side by side, so that soon the sides of adjacent ravines intersect, the doabs being then replaced by sharp ridges (Fig. 61 A). Such patterns made by parallel rills are frequently to be seen on artificial slopes of tipped debris.

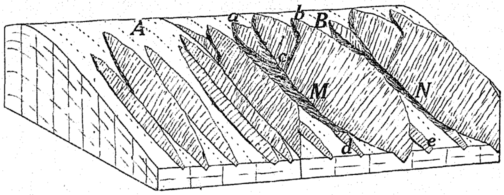


Fig. 61. Dissection of a slope by consequent streams (A); and development of master streams (B).
(From *Geomorphology,* also by the author.)

If consequent streams on a sloping surface cut deeply, some of them, favoured perhaps by the accident of draining initially larger areas, incise more deeply than do their neighbours on either hand. These become *master streams* (Fig. 61 B: *M*, *N*). As their ravines become deeper (without change of angle of their V slopes) the sides are worn back so as to cut through the ridges separating them from the smaller streams beside them, which have been left behind at higher levels, and these are compelled to run down into the valleys of the master streams as their tributaries. (Thus *a* and *b* join the master *M* at *c*.) A few master streams may soon receive practically the whole drainage of the surface (Fig. 62), though near the foot of the slope, where the master valleys are shallow and narrow ("bottle-necked"), diminutive beheaded streams (Fig. 61, *d*, *e*) will still remain, which are remnants of at least some of those that have failed in this "struggle for existence" among streams. The process of diversion of the headwaters of streams to be added as

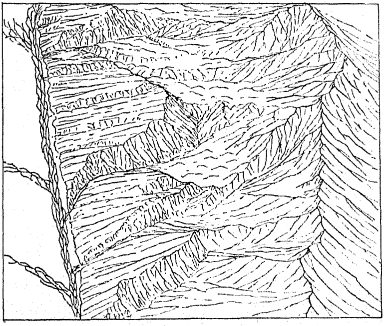
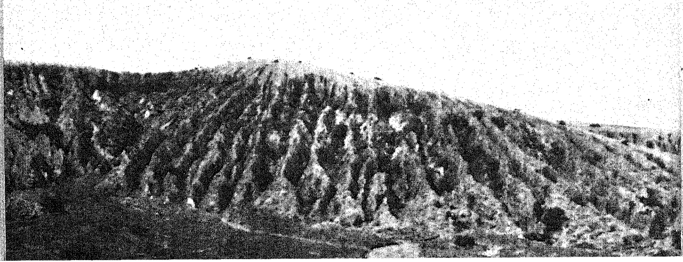


Fig. 62. Development of master streams in bottle-necked valleys on a sloping surface. Dry Canyon, Death Valley, California. (From a photograph.)

tributaries to their neighbours as a result of widening of the valleys of the latter is *abstraction* (Gilbert).[9] It is well illustrated among the very numerous "badland" ravines that have been cut by wet-weather streamlets on pumiceous debris (volcanic "mud") spread over hillslopes near Lake Rotomahana, New Zealand, by volcanic explosions (Fig. 63).

Fig. 63. Consequent gullies on a volcanic "shower" deposit spread over a hilly surface near Lake Rotomahana, New Zealand, by an eruption in 1886.



Other things being equal, plains uplifted bodily without deformation require a vastly longer time for their complete dissection than do surfaces with diversified initial relief. On such a plain, if it is underlain by unconsolidated material, most of the precipitation sinks immediately into the ground to join the ground water. Also temporary streams and sheetfloods formed on the horizontal surface are so sluggish that they do not corrade. Thus considerable areas of such surfaces may survive for a long time, even though built of soft materials. That is to say, they are stable forms, such as one may expect to find undestroyed by dissection among existing landscape features. Little-dissected extensive plains of river-laid gravel and finer materials that are trenched by main rivers but not by tributaries are in this category—for example, high parts of the Canterbury Plain (Figs. 203, 204) fringing the New Zealand Alps.

Coastal Plains and Extended Rivers

Uplifted sea floors also, if not strongly warped or tilted, are stable forms in youth. Most known examples in this stage are *coastal plains*[5] (Fig. 64) emergent as strips narrow or broad bordering pre-existing lands that have been upheaved along with them. It is usual to refer to the pre-existing land as an "old land" when it is to be contrasted with the newer land of the coastal plain, but one may avoid confusion with the use of "old" as a cycle stage by substituting "ancient land", or perhaps "hinterland".

Whether or not slight seaward tilting accompanies its uplift, as seems commonly to be the case, the surface of a coastal plain has a more or less uniform slope seaward, and is drained by more or less parallel consequent streams that take seaward courses upon it. Minor irregularities of the surface may obviously guide such streams into somewhat roundabout courses, however, and two or more may unite before reaching the sea. All the larger rivers will have their headwaters in the ancient land behind the coastal plain. They are, in fact, the rivers of that land *extended*[5] across the newly emerged surface; and, as they cross it in courses consequent on its slope, they are *extended consequents*. The larger, at least, of them carry so much water that they are competent to cut down and grade their courses very quickly wherever this may be done without cutting trenches in harder rock under the coastal-plain deposits; and this is one of those almost instantaneous occurrences that may

be expected to be completed during the time occupied by rapid uplift. Broad areas of the interfluves (doabs) between these larger rivers may, however, long remain undissected, and so young coastal plains are well-known landscape features.

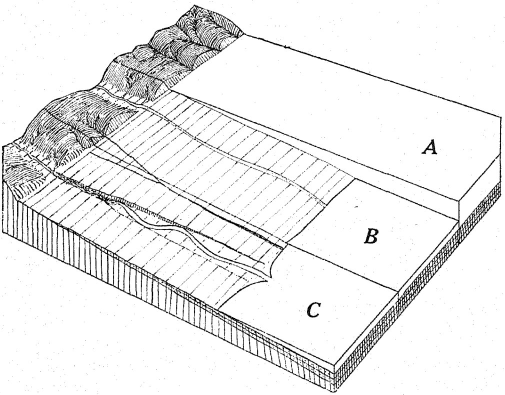


Fig. 64. A coastal plain. *A*, pre-existing land with the sea at the level of the ancient shore line; *B*, coastal plain emergent, as though the sea had suddenly withdrawn from it; *C*, coastal plain with extended river graded across it in the soft marine sediment.

(From *Geomorphology,* also by the author.)

A coastal plain forms the south-eastern seaboard of North America. It increases in breadth south-westward, and is especially broad around the Gulf of Mexico. Some parts of this coastal plain are still young, but others are maturely dissected. Instructive "pocket" examples of coastal plains fringe the coast of Japan as a result of a very recent uplift.[2] In the great bays along the south coast of Honshu, successive uplifts have caused two parallel strips of sea floor to emerge, the higher of which is somewhat dissected and the lower undissected (Fig. 65). As the hinterland is mountainous, towns and villages have been built on the coastal plains.

Available Relief

The question of the stability, or longevity in the cycle, of uplifted plains, including coastal plains, involves consideration of the concept of *available relief* due to Glock[10] and redefined by

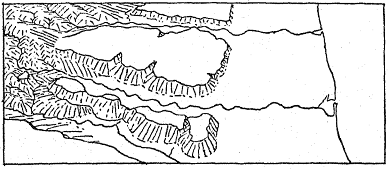


Fig. 65. Right: a very young coastal plain. Centre: a somewhat dissected coastal plain. Left: the ancient land. Osaka Bay, Japan. (After Cushing.)

Johnson.[11] Without accepting, or attempting to frame, such a definition as will make possible a precise quantitative statement of the available relief of any district, one may take it to be at any particular place and time the height of the surface undergoing dissection above the local base-level controlling dissecting streams. Obviously in the cases referred to in the two preceding paragraphs, small available relief is a factor favouring slow dissection, while with large available relief relatively rapid dissection of an uplifted plain may be expected unless rivers are very widely spaced.

The Fall Zone

As extended consequents cut down through coastal plains in the vicinity of the former shorelines, where the marine deposits underlying them usually have a thin edge, the rivers in such a case become superposed on more ancient rocks beneath this cover. Generally the rocks of the undermass are relatively resistant to erosion, and so corrasion, which has rapidly graded the rivers and opened out the valleys in their lower courses, is here checked, and the extended rivers have ungraded steep descents, with falls and rapids, in this part of their courses (Fig. 66). Where there is a row of extended rivers crossing a long coastal plain, there are generally such ungraded

superposed parts in all of them, and the line passing through these (roughly parallel to the ancient shore line) is the *fall line* (or *fall zone*).

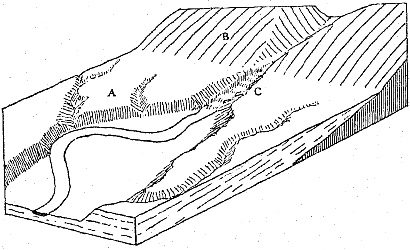


Fig. 66. Fall-line rapids in an extended river. A, coastal plain; B, ancient land; C, fall line. (After a diagram by Davis, redrawn.)

Coastal Plains not all Plains

While young coastal plains are under consideration, it may be as well to warn the reader of a pitfall dug by the adoption in geology and geomorphology of the term "coastal plain" for a feature, or rather group of features, definitely originating as the result of uplift of the sea floor. There are coastal lowlands and plains bordering the sea that have come into existence in other ways, but these are not "coastal plains" in the technical sense, though frequently they are described as such by geographers regardless of the convention adopted by geomorphologists. A coastal plain when it becomes dissected is paradoxically still, according to the usage of geomorphology, a "mature coastal plain", though it is no longer a geographical plain. This description is perhaps better phrased "maturely dissected coastal plain". The usage is an outgrowth of the peculiar use of "plain", "plateau", and "plateau structure" with purely structural significance to describe a terrain of horizontal stratified rocks* however thoroughly the terrain may be dissected.[5, 13] We read that "mature plains and plateaux" are "hilly or mountainous" country, and that "old plains or plateaux" have been worn

* Compare the use of "table-land" by Suess.[15]

down to peneplains.[13] This is on a par with the unfortunate geological practice of describing a terrain as "folded mountains" because it consists of folded strata and without reference to its present relief, which erosion may have reduced to insignificance, or which may be due to erosion induced by an upheaval of a date very much later than the folding of the strata of the terrain. Strahler,[14] who has criticised the use of the words "plains", "plateaux", and "mountains" in the description of structures of the terrain, continues to use "coastal plain" with the usual structural significance and implication regarding geological history. It is realised that adverse criticism of so well established a geological usage would be wasted effort.

Headward Erosion

Besides systems of consequent valleys and any others that may have been present since infancy on a young uplifted surface, more are developed on it and share in its dissection. They are cut by new streams that come into existence in the course of dissection and can be classed mainly in two categories, "insequent" and "subsequent". Streams of these classes have this in common, that they extend or grow in length headward, or by *headward erosion*, deepening valleys for themselves as they extend. "Insequent" is a term invented by W. M. Davis,[7] who also adopted "subsequent", as previously used by Jukes.[12] "Obsequent", meaning opposite to consequent, is another description for streams that was invented by Davis. It can be applied only in rare cases where it appears that reversal of the direction of drainage on a part of the surface has taken place during the lowering of the land by erosion. Many streams have been rashly and probably erroneously classed as obsequent, as Baulig[1] has pointed out, though all that is known about them is that they flow in the direction opposite to the dip of the strata, or are anaclinal.

Insequent Streams

Insequent streams develop in great numbers in the course of the dissection of level upland surfaces (including coastal plains) underlain by fairly homogeneous material or horizontally bedded formations, and in soft materials may extend headward very rapidly. They may start as precipitous ravines cut by concentrated rain-wash collecting in any slight hollows that have been accidentally formed

in haphazard positions on the sides of main valleys, perhaps where rock slides have occurred. They are thus generally tributaries, but independent insequents may develop in cliffs bordering the sea. As the gullies grow longer and deeper they receive an increasing amount of water both from the run-off and from ground water sinking into the level upland and now seeping out along the banks and around the steep heads of the young insequent ravines. Thus headward erosion is accelerated. Insequent streams are without guidance as to the directions in which their heads extend, unless a greater volume of ground water seeping in from one side may cause headward deflection in that direction. This may perhaps explain the tendency of many insequent streams to head up any slope the initial surface may have.

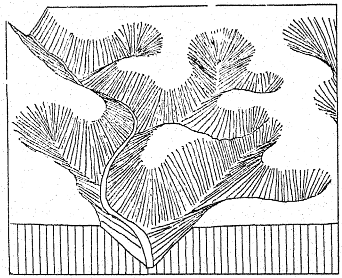


Fig. 67. Insequent dissection. (After a diagram by Davis, redrawn.)

The first-formed insequents in their turn develop insequent tributaries, and as these also work their way headward into the doabs (interfluves) the area of undissected surface is reduced with increasing rapidity (Fig. 67). On the coastal plain of eastern Italy (Fig. 68) doabs have been destroyed and replaced by round-crested ridges and spurs, and dissection is *mature*. The streams dissecting such a "mature coastal plain" are extended consequents, new consequents, and insequents.

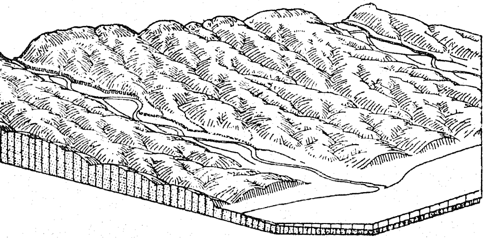
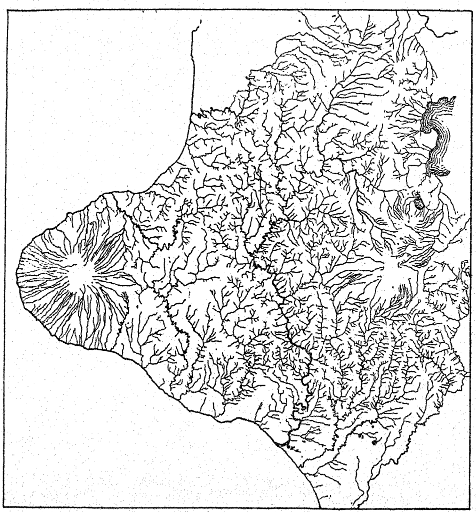


Fig. 68. Maturely dissected coastal plain of eastern Italy. (After Davis.) (From *Geomorphology*, also by the author.)



g. 69. Insequent drainage pattern exhibited by the tributaries of the Wanganui and neighbouring rivers (New Zealand). Compare this (central area of map) with the patterns of radial consequents on the volcanic mountains Egmont (west) and Ruapehu (east). (After Marshall: *Geology of New Zealand*.) (From *Geomorphology*, also by the author.)

Dendritic Pattern

The river pattern, as seen on a map, that results from development of insequent drainage, has been likened to the branching of an apple tree, and called *dendritic*. A broad strip of the North Island of New Zealand, drained by the Wanganui and several other consequent rivers with many insequent branching tributaries, exemplifies well the dendritic pattern (Fig. 69). This district is underlain by soft marine formations of great thickness, and is nearly all maturely dissected to sharp ridges and spurs by streams, most of which are not yet graded throughout their lengths.

Law of Equal Declivities

Where homogeneous rocks are maturely dissected by consequent and insequent streams, as in the examples cited above, the side slopes of the valleys—that is to say, all the hillside slopes—tend to develop at the same angle, so that ridges, spurs, and valleys assume symmetrical transverse profiles except where such symmetry is interfered with by the effects of lateral stream corrasion developing contrasted undercut and slip-off slopes around valley curves. This is Gilbert's *law of equal declivities.*[9] It was stated by him as though slopes were developed entirely by streams of water running down their declivities, but is true, nevertheless, as applied to the sum of the effects of the processes of rain-wash, soil creep, etc., that are reducing land slopes to gentler declivities, as is proved by the constant recurrence of symmetry in landforms on homogeneous and horizontally bedded rocks.

In homogeneous material, and with equal quantities of water, the rate of erosion of two slopes depends on their declivities. The steeper is degraded the faster. It is evident that when two slopes are on opposite sides of a divide the more rapid wearing of the steeper carries the divide toward the side of the gentler. The action ceases and the divide becomes stationary only when the profile of the divide has been rendered symmetric. (Gilbert)[9]

Subsequent Rivers

Subsequent rivers come into existence during the process of dissection, and these, like those described as insequent, owe their extension to headward erosion, guided in this case, however, by

the outcrops of weak rocks occurring as strips or broader belts. Obviously the nature of the rock, whether weak or resistant, determines the rate at which gullies can develop and be extended headward by erosion. Where the rocks are all equally resistant (or uniformly weak), insequent streams come into existence and branch in all directions impartially; but where a main stream crosses zones of alternately weak and resistant rocks, tributary streams that begin to nibble back on the outcrops of weak rocks are enormously favoured thereby, and the development of new streams on the resistant rocks may take place so slowly in comparison as to be negligible. It is the tributaries that start on the weaker outcrops and are afterwards confined to and guided in the direction of their headward erosion by weaker zones of rock that are chiefly effective in dissecting the land surface. These are *subsequent*,[7, 11] and the divides between them are *subsequent divides* (Fig. 70). So rapidly

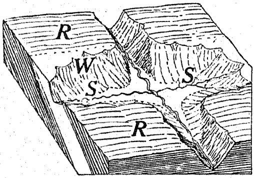


Fig. 70. A hypothetical early stage in the development of valleys by newly formed subsequent streams, *S*; on a weak belt of rocks, *W*; between resistant belts, *R*. (From *Geomorphology*, also by the author.)

do subsequent valleys develop that the intermediate "cuesta-bridge" stage,[8] as shown at the right in Fig. 70, appears not to be represented by an example in any dissected coastal plain or similar landscape.

Where weak formations outcrop as continuous belts, subsequents develop along them rapidly and become graded almost at once with respect to the levels of the main streams at their junctions, which are local base-levels for the tributaries. (In fact, the level of every point on a river may be regarded as a local base-level for the river above that point with all its tributaries. It is a fluctuating level, however, rising or sinking as the river aggrades or degrades its

valley.) With the exception of some that are located on the crush zones, sometimes termed "shatter belts", of faults, which may have any accidental orientation, weak formations are usually members of inclined series of strata, in which weaker and more resistant layers occur alternately, with parallel outcrops. Subsequent divides become more or less prominent ridges of the resistant members of the series, and both these and the subsequent valleys are elongated in the direction of the geological *strike*.

The term "subsequent" does not fully describe the origin of the features to which it is applied, and might be considered to include those classed as insequent. It merely indicates an origin at a date subsequent to the initiation of consequent drainage. It is usefully, though arbitrarily, restricted in application to those erosional features the lines of which have been determined by structures of the terrain (whereas insequents are not so guided). Without abandoning this conventional use of "subsequent" altogether, it is sometimes convenient to describe valleys (and ridges also) that are aligned on the outcrops of inclined strata as "strike" or simply as "longitudinal" features; for quite probably no longitudinal consequent rivers survive in terrains of rather strongly inclined and folded strata (pp. 114-5), and so (as long as this is recognised) there will be no ambiguity.

Where, as is usually the case, longitudinal subsequent rivers develop as tributaries, the mains must be transverse. Such main rivers may be antecedent, superposed, or even in some cases deeply cut consequents of a first cycle. These transverse rivers may still have ungraded gorges, where they cross resistant rocks, but the subsequent tributaries that join them in graded reaches farther upstream may be thoroughly graded, having no hard-rock difficulties to contend with. Such, for example, are the tributaries of the Hunho system of North China (Fig. 56). The main river is literally "held up" for a relatively long period by the resistant-rock barrier through which it must laboriously deepen its gorge. As it does so an upstream subsequent tributary easily lowers the floor of its already graded and open valley to an accordant depth.

The valley of a subsequent river on a belt of weak rocks soon becomes widely opened, and simultaneously the denudational surface-lowering processes acting over the whole breadth of the belt reduce it to low relief as compared with steep and less fully mature forms

of high relief that still survive on adjacent hard-rock belts. Thus elongated *subsequent lowlands* are developed (Fig. 71), through which subsequent rivers take leisurely courses, and locally on weak-rock belts a far "older" stage of landscape development will be found than on alternating hard-rock belts.

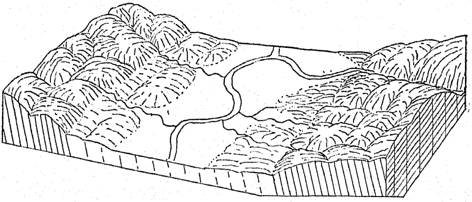


Fig. 71. A subsequent lowland on a belt of weak rocks.

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CHAPTER VIII

Shifting Divides and River Piracy

ON A MATURE SURFACE DIVIDES ARE WELL DEFINED AND SO CONTRAST strongly with the very poorly defined divides generally present on the same surface while it is still young. The well-defined divides of maturity are, however, by no means fixed in position for all time, but shift laterally, and in some special cases migrate rapidly and far. Being defined by the intersections of slopes of adjacent valley sides, they are liable to displacement as the result of any changes in these slopes, and especially as the result of more rapid valley deepening on one side than on the other.

CREEPING AND LEAPING DIVIDES

Such slow migration (Fig. 72) is *creeping*; but, should diversion by abstraction of one stream into the system of its neighbour take place, the result is *leaping,* for the whole headwater drainage system of the abstracted stream is transferred in a moment and added to that of the other. There is no longer a divide between them. (In Fig. 72 this takes place if the creeping of *E* towards *A*

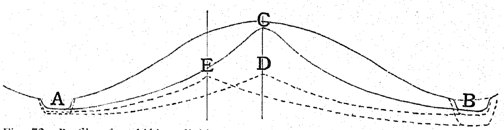

Fig. 72. Profile of a shifting divide. *C*, original position of the divide; *D*, possible later position after some lowering of relief; *E*, another possible position, where lateral shift has taken place because valley *B* has been deepened more rapidly than *A*.

(From *Geomorphology,* also by the author.)

goes on until the stream *A* is abstracted and flows down the slope *EB* into *B*.)

Even a main divide along the crest of a mountain range may slowly migrate an appreciable distance, and some have obviously

done so as a result of more rapid erosion on one side of the range than on the other. The reasons for this may be quite unconnected with rock structures, or with differences of rock hardness, which are capable of causing migration and will be considered later. One cause of migration is found where rivers on one side of a range have much shorter courses to the sea than have those on the other side. A classical example of this is the retreat that has taken place of

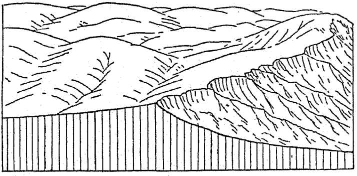

Fig. 73. The scarp of the Blue "Ridge", North Carolina. (After Davis.)

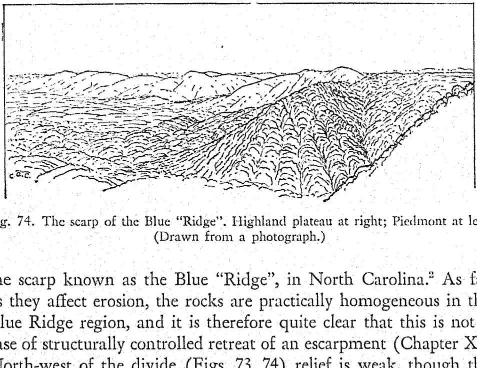

Fig. 74. The scarp of the Blue "Ridge". Highland plateau at right; Piedmont at left. (Drawn from a photograph.)

the scarp known as the Blue "Ridge", in North Carolina.[2] As far as they affect erosion, the rocks are practically homogeneous in the Blue Ridge region, and it is therefore quite clear that this is not a case of structurally controlled retreat of an escarpment (Chapter X). North-west of the divide (Figs. 73, 74) relief is weak, though the land surface is high above the sea, for the streams on it are head-waters of members of the Mississippi system, and their waters

follow a long and somewhat roundabout route to the sea. The descent, on the other hand, south-eastward from the divide is so steep as to be almost wall-like, with a drop of 1500 feet to the heads of the streams on the Piedmont, at the rear of the Atlantic coastal plain, whose courses to the sea are comparatively short.

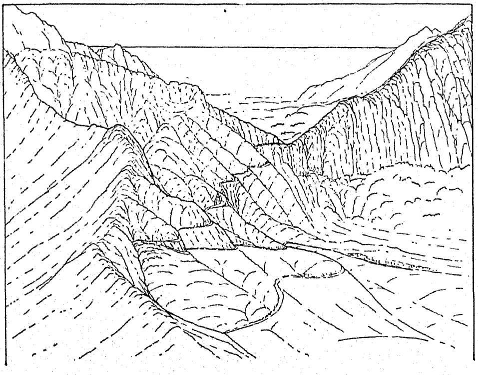

Fig. 75. Shifting divide between the head of Nuuanu valley (in the distance, through the gap) and the Pali (meaning "cliff"), Koolau Range, Oahu, Hawaiian Islands. View south-westward. (Drawn from a photograph.)

A major landscape feature very similar to the Blue Ridge scarp is that portion of the "Great Escarpment" of southern Africa which forms the wall-like Drakensberg in Natal. This is not a "structural" escarpment throughout in the sense of marking the outcropping edge of a sheet of hard rocks. Though a portion of it is of this nature, bounding the high plateau of Basutoland, farther north in Natal the crestline of this continuous scarp is no more than the asymmetrical and vigorously migrating divide between long, sluggish, westward-draining rivers on the High Veld, a vast peneplain, and the headwaters of shorter rivers descending to a narrower eastern marginal peneplain approximately of the same age which is developing at a lower level because it is near the ocean.[4]

Similar migration of the crestline divides of mountainous islands in the trade-wind belts may take place, for here there is heavy precipitation on the windward side, while the lee side is relatively rainless. An example of this kind is found on the island of Oahu, Hawaiian Islands (Figs. 75, 76), where the north-eastern half of the Koolau Range has been entirely destroyed by deep erosion and the crestline has been forced back south-westward towards the leeward side of the range, the slope of which is only moderately dissected.[7] The line of cliffs descending north-eastward from the divide is known as "the Pali".

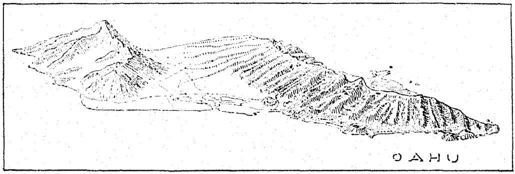

Fig. 76. Oahu, Hawaiian Islands, from the south. At the right (east) is the crescentic remnant of the Koolau Range. (After C. K. Wentworth.)

Shifting takes place also of the divides between the opposed heads of rivers, and may be pushed rapidly and very far where these are subsequents developed or developing on the same weak belt of outcrops. Proofs of such rapid migration of the divide between opposed streams may sometimes be seen if remnants of valley-floor

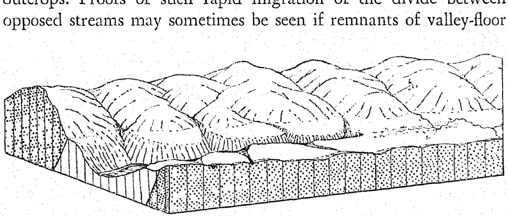

Fig. 77. Creeping divide between the heads of subsequent rivers on a belt of weak rock. Remnants of the valley floor of the now shrunken river on the right now border the more vigorous river flowing to the left, which is extending its valley by headward erosion.

(From *Geomorphology*, also by the author.)

gravels of the weaker stream, or of the valley floor itself, are left as terraces with up-valley slope bordering the narrower and more newly cut valley of its more vigorous competitor (Fig. 77).

The weaker stream, having been robbed of its headwaters and any headwater tributaries it may have had, is now of diminished volume. So the valley bottom near the divide will probably be swampy.

A well-known example of a creeping divide of this kind is that in northern France between the head of the Bar, which is being pushed back, and a tributary of the Aire, which is more vigorous

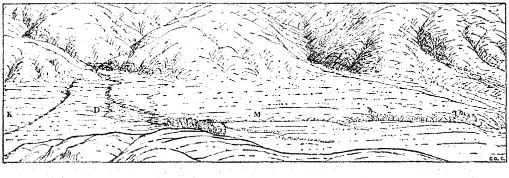

Fig. 78. Low divide (at D) between subsequent valley-heads of the southward-flowing west branch of the Karori stream (K) and the northward-flowing Makara stream (M), near Wellington, New Zealand. (From photographs by Maxwell Gage.)

as a result of recent deepening of the valley of the Aire itself (Fig. 85, *A*). On the ill-defined divide between the heads of the Bar and the Aire tributary, the last diversion of an incoming side stream from the shrinking Bar system was hastened artificially in the eighteenth century. A very similar creeping divide separates the heads of the western Karori and Makara, near Wellington, New Zealand (Fig. 78), though in this case it seems that the encroaching stream (Karori) has been invigorated by land warping which has steepened its course.[3] The divide is low and ill-defined and is creeping northward, a side stream of the Makara that enters it from the west being now in danger of transference to the Karori system.

River Capture

Diversion of streams by abstraction as a part of the process of development of master consequents, as already described, is only one of several ways in which such changes in river courses are

brought about. Diversion of headwater streams to become tributaries of other rivers is generally termed *capture*, and the diminished lower courses of the former rivers, where they survive at all, are

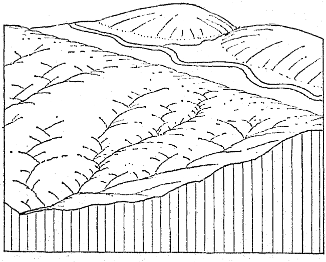

Fig. 79. A high-level river threatened with capture by a developing insequent stream. (After a diagram by Davis.)

beheaded. "River capture" may be understood as including abstraction, but is sometimes limited in its application to a process of diversion by streams developing headward at a rapid rate under certain favourable conditions so as to tap and lead off the waters of others. This process has been called also "river piracy".

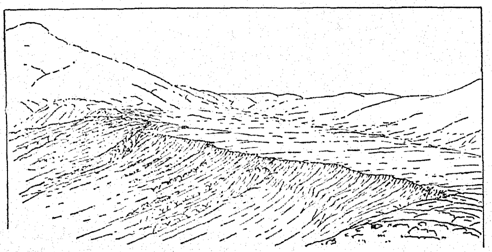

Fig. 80. A tributary of Clark Fork (left) threatens to capture Rock Creek (right), towards which a divide (across centre) is creeping. Big Horn Basin, Wyoming, described by Mackin. (Drawn from a photograph.)

The most favourable condition for capture to take place is that a stream with an outlet at a relatively low local base-level shall be developing by headward erosion and pushing the divide at its head towards a river that flows at a higher level, being perhaps held up by a hard-rock barrier it has to cut through in its lower course, or following a roundabout route to the sea (Figs. 79, 80, 81).

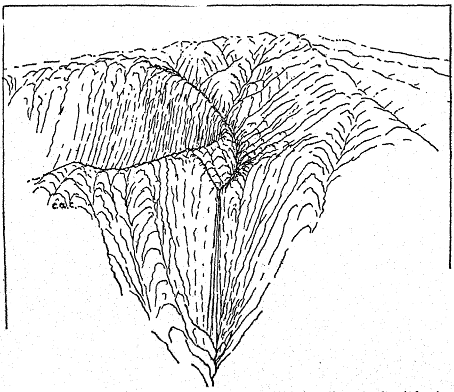

Fig. 81. The rapidly developing amphitheatre-headed valley at the left threatens to capture the headwater stream in the V-shaped valley (centre) above the waterfall. Maui, Hawaiian Islands. (Drawn from a photograph.)

Another condition favouring capture is found where one stream has a heavier load of waste than its neighbour, perhaps because it emerges from a mountain valley and carries coarse gravel. The more heavily loaded stream will have a steeper gradient, and at an equal distance from its mouth will flow at a higher level, than the adjacent stream which carries less (and finer) waste, and is liable to be captured by the latter. Captures due to this cause have been noted by Rich[6] at the Book Cliffs escarpment, Utah, and by Mackin[5] in the Greybull River, Wyoming.

The stream that effects a capture may be insequent or subsequent; but it is most often subsequent streams that succeed in making captures and transverse streams that are beheaded, for the former extend headward rapidly, and develop uniformly graded gentle declivities, while the deepening of the latter is delayed until they can grade their hard-rock gorges farther downstream. In

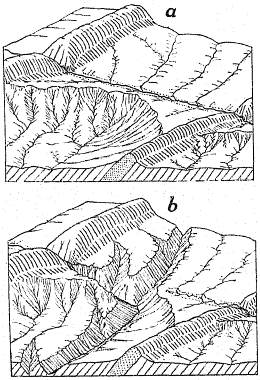

Fig. 82. Diagrams illustrating capture of the headwaters of one transverse stream by a subsequent tributary of another. In stage *a* capture is imminent; while in stage *b* it has taken place. (After a diagram by W. M. Davis, redrawn.) (From *Geomorphology*, also by the author.)

Fig. 82, *a*, a transverse river is threatened with capture by a subsequent that may be regarded as a tributary of another transverse river, the latter being larger and having, therefore, a more deeply cut valley than the threatened stream. In Fig. 82, *b*, the former upper course of the transverse river has been captured and added to the valley system of its nearby competitor, as a result of continued headward erosion of the *diverter*, as it has now become. What remains of the transverse river is a beheaded stream. Before capture took place the divide between the would-be diverter and any former tributary of the river threatened with capture that existed on the

same weak belt may have crept a long distance (after the manner of the creeping illustrated in Fig. 77) before capture became imminent. Towards the end of the process such creeping is accelerated as the volume of the diverter is augmented by seepage of ground water fed by leakage through the bed of the threatened river.

The right-angle turn that a captured transverse river makes at the point of diversion (Fig. 82) is termed the *elbow of capture*. It would be a mistake, however, to assume that all right-angle turns in river courses, as shown on maps, indicate that captures have occurred, for many such turns, especially in block-faulted regions, are of consequent origin. Still, when other indications of recent capture have been smoothed out of the landscape by long-continued erosion, a suspected elbow of capture appropriately located as regards underlying structures may be the only remaining evidence of a diversion that has occurred in the distant past. Nor should the absence of a conspicuous elbow lead to the rejection of a theory of capture founded on other good grounds, for, obviously, an elbow is a feature of the capture of transverse streams only.

Recent captures are very easily identified by an association of special features that develop rapidly and conspicuously in consequence of the event. Changes occur in stream profiles, because the valley of the diverter, though graded or nearly so for the volume of water it was formerly carrying, is much too steep after diversion takes place for the enlarged stream that now flows in it. This is the case especially at its former head—that is, in the vicinity of the elbow or point of capture. So degradation begins, and a youthful trench is cut by the diverter; and this extends headward up the captured river, which has for a time (until regraded) to flow down a steep slope into the diverter. Tributary streams joining the newly entrenched part of the river must also deepen their valleys anew as their local base-level (the level of the main stream) is progressively lowered (Fig. 82, *b*).

Air Gaps

In course of time, when the deepened trench at the point of capture is widened also, the new divide between the captured and beheaded portions of the former river is pushed back so as to shorten the beheaded stream still further, and in the case of a

beheaded transverse river, its head is gradually transferred to the outcrop of the next resistant stratum downstream. The former gorge through this outcrop, still a "water gap" in Fig. 82, *b*, when no longer traversed by a stream, becomes an "air gap" or "wind

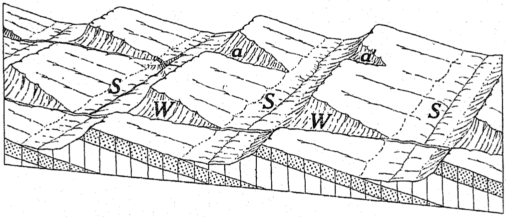

Fig. 83. Air gaps indicating former captures. *W*, water gaps; *a*, *a'*, air gaps; *S*, subsequent valleys.
(From *Geomorphology*, also by the author.)

gap" (Fig. 83, *a*, and Fig. 84). When the floors of adjacent valleys are further lowered by subsequent erosion, such an air gap may remain as a mere notch in the skyline of a subsequent ridge (Fig. 83, *a'*). While a capture is still of recent occurrence (Fig. 82, *b*) the new head of the beheaded stream is usually poorly defined, however, for it now rises in a swampy flat that was part of its valley floor before its headwaters were diverted.

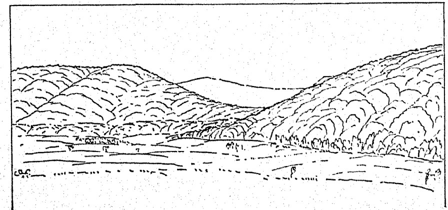

Fig. 84. Air gap in Sallings Mountain ridge, Virginia, 400 ft. above the adjacent lowland; described by F. J. Wright. (Drawn from a photograph.)

Here, and downstream also, the river will show characteristic effects of substantial reduction of volume, which makes it too small for its valley, or "underfit". Special features of the valleys of underfit rivers (not all of which have been beheaded by capture) will be discussed in Chapter XII.

Beheaded Rivers

Perhaps the best-known examples of rivers that have been beheaded by capture are the tributaries of the Meuse, of which it has been robbed by members of the Moselle system on the one side and the Seine on the other[1] (Fig. 85). The Aire, whose waters go now by way of the Aisne to the Seine, was formerly the head of the now shrunken Bar, a tributary of the Meuse, while what is now the head of the Moselle formerly, and rather recently, passed through a now abandoned valley from Toul to Pagny, where it joined the Meuse. In the latter example the elbow of capture, near Toul, is very sharp.

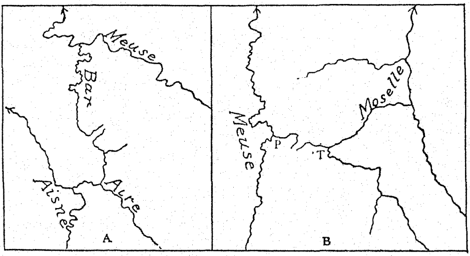

Fig. 85. Captures. *A*, the Bar is beheaded, and its headwaters (as the Aire) are added to the Aisne; *B*, a former tributary of the Meuse becomes the head of the Moselle; *T*, elbow of capture, at Toul; *P*, Pagny.

A small example of capture at Wellington, New Zealand, presents all the features of recent capture (with the one exception of the non-essential elbow of capture) very closely grouped, so that they are seen in a single view (Fig. 86). The diverter and captured

stream in this case are strictly in line (Fig. 87), because both have been developed, the captured stream first and the diverter later, by valley-making processes, including erosion, on the same fault zone. This weak zone was occupied formerly by the headwaters *ab* of the

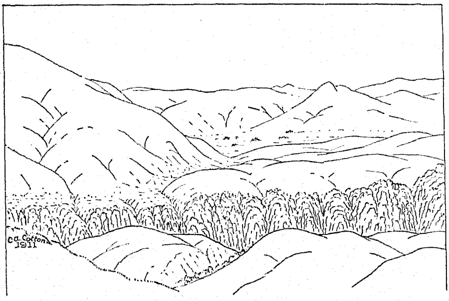

Fig. 86. The Kaiwarra capture, Wellington, N.Z. Diverter (right) and captured stream (left) are deeply entrenched. The former level of the latter is indicated by the terrace (left); and accordant with this is the abandoned course through an air gap (centre; middle distance).

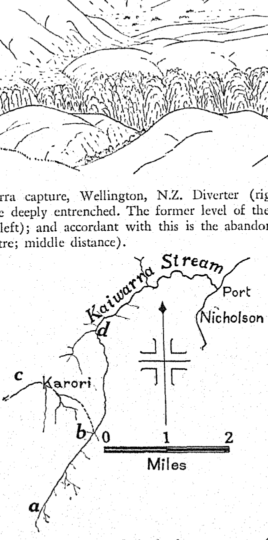

Fig. 87. Map of the Kaiwarra capture; *abc* is the former course of the Karori Stream, since diverted at *b*.

(From *Geomorphology*, also by the author.)

Karori Stream, which, however, left the fault line at *b*. Later the insequent head of the Kaiwarra, eroding headward from *d*, discovered the shatter belt half a mile north-east of *b*, and, working back along it as a subsequent to *b*, captured at that point the former head of the Karori. The Kaiwarra was favoured by having a much shorter course to the sea than the Karori.

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CHAPTER IX

Subsequent Erosion on Folded Rocks

When it has been necessary in the preceding chapters to refer to steeply inclined strata in their relation to subsequent features and transverse valleys, the assumption has been made that rock formations in homoclinal* attitudes and with folded structures would underlie an initial surface only if inherited from some former relief.

Homoclinal Structure

Development of subsequent rivers and divides takes place in a first cycle on simple structures such as have been postulated in Chapter IV only in the special case of coastal plains that emerge with some initial dip of their underlying strata. In this case consequent streams flow in the same direction as the strata dip and are transverse to their strike, and when dissection is mature there may be considerable development of subsequent valleys and divides parallel to the margin of the ancient land, between it and the new shoreline. A "belted coastal plain" (Davis)[3] results.

Folded Rocks

The case has now to be examined, however, in which initial upheaval is accompanied by close folding, with development of steep dips (Fig. 88). The primary consequents might be expected to follow courses corresponding to the axes of synclines, for in these positions are the theoretical furrows of the initial surface, and such streams would, therefore, be longitudinal, or parallel to the general direction of the strike of the strata. The Jura Mountains are still drained in part by longitudinal streams that have been regarded as originating in this way as consequents of the first cycle, though the range has been eroded in more than one cycle.

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* The term "homocline" (introduced by R. A. Daly in 1916) replaces the ambiguous "monocline" where it is used to signify a succession of strata dipping continuously in one direction, and has been very widely adopted.

"Fold" Mountains in their First Cycle

In most regions of folded rocks, however, longitudinal or primary consequents, and indeed all consequents, have long since been eliminated from the landscape. They may perhaps be better relegated to a category of forms to be ascribed to certain hypothetical stages of infancy and youth of the landscape cycle never realised in nature among mountains of closely folded rocks. Rapid

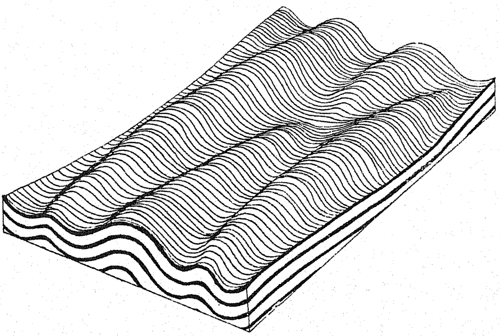

Fig. 88. An initial surface on folded rocks.
(From *Geomorphology*, also by the author.)

destruction of initial forms must indeed go on during the early stages of upheaval in folds, and must be complete long before upheaval ceases, however rapid the earth movements may be. In the study of erosion on some simpler structures it is often convenient to make a harmless, though unrealistic, assumption that upheaval completes its work of preparation of initial forms of mountains or plateaux so rapidly that the processes of erosion do not appreciably alter them during their growth, or that the commencement of erosion is magically delayed until the process of upheaval is complete. In the present case, however, this simple assumption must be discarded and the fact faced that vast erosion accompanies the upheaval of a welt of folded rocks.

The forms of youth on the huge amorphous pile of heterogeneous form and substance over closely folded structures are unimaginable, and one cannot think of this pile as a mountain range until it begins to present features of early maturity. Any hypothetical initial or infantile forms one may conjure up for such a pile of folds have never had real existence as mountains. Even where structures are less disordered, and folds more symmetrical, the processes of upheaval were building features that would have been, if they could have escaped contemporaneous erosion, totally different from those of any actual mountains. Such features, if they could have been preserved for our inspection, though higher and in some cases more symmetrical in form, would not present the diversity and grandeur of real mountain scenery.

The restored and theoretically unworn initial form of a range must be an immense pile of crowded, squeezed, and broken arches of rock. At a later time, after deep erosion has taken place, the limits of the range, though not its height, may be expected to correspond with the limits of this composite arch, but no agreement may be looked for between hypothetical surface forms of individual arches and the details of mountain peaks. The mountains, even in the early stage of maturity into which such initial forms would be sculptured as they rose, must have been very different in their general aspect, in drainage pattern, and in all details from mountains that exist in the same regions to-day. Present-day mountains on folded and overthrust rock structures may be likened to the ruined foundations of ancient lofty buildings, all the superstructures of which have crumbled to decay.

The foregoing remarks apply in particular to "fold" mountains rather than to "block" mountains, if one may revert temporarily to an outworn classification of mountain types, for block mountains (Chapter XX) may preserve fairly well, or at least vividly suggest, the broad outlines of their initial forms. Most block mountains are, however, mere incidental features of the *re-uplift* of a folded mass, or *welt,* as it is termed by Bucher.[1]

Not many years ago all the great mountain ranges of the world that are carved out of folded rocks were believed to have originated as "fold" mountains, which implied that they were now in process of reduction by erosion for the first time, or were *one-cycle* mountains. The immensity of the time interval that has elapsed since the

period of folding of even the younger (as regards date of folding) of mountain ranges is now better realised, however, and the time required for the destruction of strong relief even on the most resistant rocks can be but a fraction of this, even when allowance is made for the succession of regional uplifts (or long-continuing regional uplift), which, according to the doctrine of isostasy, must accompany the degradation of the initially upheaved welt.

It is quite conceivable that the mountains formed by the original folding were not nearly as high as a reconstruction of their piled-up folded structures might suggest. The piling together of rock folds does not necessarily form initially a very great bulge on the earth's surface, for the folded rocks are probably thrust downward as well as upward, room being made for them by lateral flow of a relatively heavy "substratum". The welt of light rocks may indeed take some time to float up and emerge as a protuberance.[15] As this is reduced in height by erosion, however, the whole folded mass must continue to rise to maintain isostatic equilibrium,[10] and so will be eroded to a depth considerably greater than the height of the original range.

Multi-cycle Mountains

In every mountain range of folded rocks that has been critically examined, moreover, evidence has come to light to prove that the mountains as they exist to-day are in reality dissected plateaux. They are *two-cycle*, or perhaps *multi-cycle*, mountains, the region having been since the folding worn down by erosion to fairly low relief at least once, and probably more than once, prior to the upheaval, generally a broad upwarping, that has introduced the current cycle of deep and mature dissection. In the Atlas Mountains, for example, evidence, long overlooked, that the modern mountains owe their relief to very recent upheaval of a peneplain truncating the folded strata and also the relief that was developed on the "Alpine" orogenic structure in the first cycle has quite recently been pointed out.[11] Such later, broadly domed uplift, affecting the folded mass and also the surrounding region, has been suggestively correlated with the original folding paroxysm as a necessary after-effect.[10]

Mountains that have passed through a stage of peneplanation in the course of their development may be recognisable as such owing to the preservation as plateaux or plateau remnants of parts of the peneplain that was the initial form of the cycle of erosion now

current. Such a surface is dissected infinitely more slowly than are the tumbled crests of an upheaved pile of folds. Those parts of it that are evenly uplifted are encroached upon by erosion only little by little as dissection proceeds, surviving longest where underlain by the most resistent rocks or where situated farthest from the main rivers. It is justifiable to suspect that mountain ranges on which no peneplain remnants are found have also had a multi-cycle origin, and the suspicion often receives a considerable amount of confirmation from an accordance of summit levels, which suggests restoration of a peneplain destroyed by erosion but formerly existing a little above the summits of many surviving peaks (Chapter XVI).

In the Alps of Europe

> the folding of the strata is not the direct cause of the present mountain range, but . . . the latter came into existence later by elevation. . . . We have distinct proof in the structure of these mountain ranges that folding is not the necessary corollary of mountain-making even in the Alps and that the more elevated parts of the Alps owe their height to a vertical movement of the earth's crust. . . . Recent investigations have shown that the vertical movement which caused the elevation was very considerable even in the . . . Pleistocene. These proofs are given by the surface features of the mountains. . . . The mountain region which had just been elevated had some other surface features than the Alps of to-day. The mountains were not so high; their forms were more rounded; their valleys were broader and not so deep as to-day (PENCK).[14]

ADJUSTMENT TO STRUCTURE

The present problem is to deduce a reasonable concept of the erosion of a folded mass in its first cycle, and this may be done in terms of the deduced process of destruction of a simplified initial surface with strong corrugation above folds of similar form, such as is shown in Fig. 88. It may be assumed that the hypothetical longitudinal or primary consequents in the synclines of the surface will be fed by tributaries—secondary consequents—running down the flanks of the initial arches, and thus in the directions of dip of the anticlinal strata. As they flow down steep slopes, such streams will degrade rapidly and soon cut deep trenches; and where, in their down-cutting, they expose outcrops of weak strata they will send out along them other tributaries developing headward as

subsequents on the weak-rock outcrops. In the diagram (Fig. 89) *A* represents the initial form, while surfaces *B* and *C* are developed in successive stages of erosion. Subsequent valleys and ridges will develop apace, and innumerable captures will divert the waters of secondary consequents into new courses, so that both secondary and primary consequents dwindle.

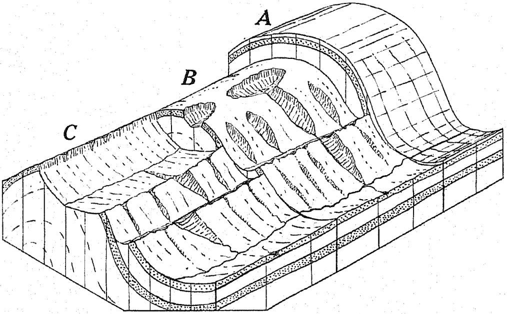

Fig. 89. Development of subsequent drainage on folded rocks. (From *Geomorphology,* also by the author.)

Consequent features must be so ephemeral in the development of drainage forms on folded rocks that one need not expect to find the stages of their replacement by subsequents illustrated by examples in actual landscapes, though some features of the valleys of the Jura Mountains have been, perhaps mistakenly, so interpreted. Very high longitudinal features of the mountain ranges of southwestern Iran, which are composed of openly folded strata, are consequent, according to the interpretation of their geological history offered by Harrison and Falcon,[9] but such a survival of one-cycle mountains from the Alpine folding period, if it can be substantiated, must be quite exceptional. As Powell has remarked: "Geologically all existing mountains are recent; the ancient mountains are gone".

Though the foregoing deduction of early stages of the development of drainage may be pure hypothesis, there can be no doubt that at some early stage of the erosional history of a mass of folded stratified rocks subsequents extend headward along all suitably

exposed belts of weak material, at the expense of streams of all other types that may be present, causing these to shrink in length and volume as they are robbed of their headwaters and tributaries. The general process that results in the transfer of the bulk of the drainage to streams in subsequent valleys on weak zones is *adjustment to structure* (Davis).[2, 4, 5] Beginning in the stage of youth of a first cycle, if not yet perfectly developed it continues in maturity of the landscape, and in later cycles. An example of adjusted drainage is the Hunho valley system of North China, described by Barbour (Fig. 56).

Trellised Drainage

The drainage pattern that results from adjustment appears on a map as a system of subparallel rivers aligned on the strike of the rock formations in a general way, but making occasional right-angle turns to cross strike ridges (generally in gorges) (Fig. 90). This is

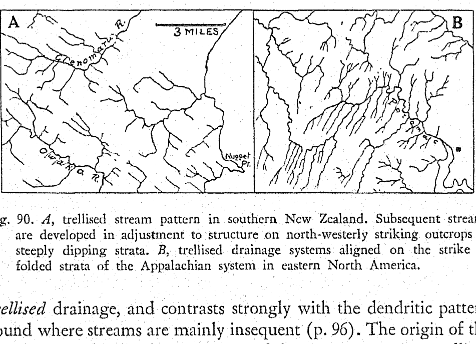

Fig. 90. *A*, trellised stream pattern in southern New Zealand. Subsequent streams are developed in adjustment to structure on north-westerly striking outcrops of steeply dipping strata. *B*, trellised drainage systems aligned on the strike of folded strata of the Appalachian system in eastern North America.

trellised drainage, and contrasts strongly with the dendritic pattern found where streams are mainly insequent (p. 96). The origin of the transverse, generally short, portions of the river courses in a trellised pattern, in which the rivers break through the outcropping edges of resistant formations, is usually obscure, and especially so if the surface has been subject to erosion in more than one cycle. Some of these may possibly be relics of secondary consequents of a first cycle, as suggested in Fig. 89, and others of primary consequents that

might cross low sags in the crests of initial anticlines, as suggested in Fig. 88; but parts of antecedent and superposed river courses are just as likely to be present in the transverse reaches of many trellised patterns. The longitudinal members will be quite parallel

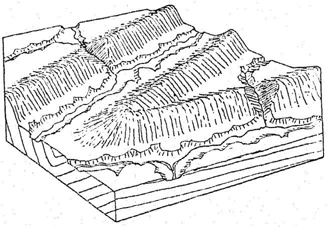

Fig. 91. Strike ridges, with two meeting in the form of a V, as developed in the Allegheny Mountains. (After a diagram by W. M. Davis, redrawn.)

only on the simplest folded structures, but on pitching folds they will converge; while the dividing ridges, situated on the outcrops of the harder strata, will assume V-forms in plan (Fig. 91) or curve around in canoe-end shapes (Fig. 92).

In mountainous regions of folded rocks erosion has proceeded to such a great depth below the hypothetical initial surface that no survivals of tectonic forms such as anticlinal ridges may be expected to occur; and even in a first cycle such forms must have been very unstable and prone to destruction.[8, 13] Being initially high above

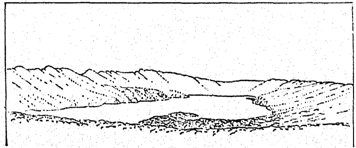

Fig. 92. Dip slope of an outcrop ridge (Mt Difficult Range), curving around with the strike in a pitching syncline; Wartook Reservoir, Victoria, Australia. (After a sketch by E. S. Hills, redrawn.)

local base-levels and flanked by steep surface slopes in the direction of the inclination of the strata, they would tend to collapse by rock sliding as soon as the primary consequent valleys in adjacent synclines began to be deepened by erosion (Fig. 93). In Persia some remarkable cases have been reported of a large-scale superficial peeling-off and slow down-creeping as recurved flaps of upper limestone strata from the flanks of high mountain ridges with an open and symmetrical anticlinal structure.[9]

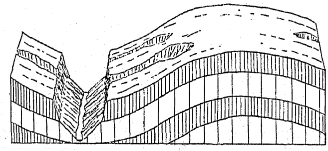

Fig. 93. Conditions of structure and incipient erosion favouring destruction of an anticlinal ridge by rock sliding in a first cycle.

Synclinal Mountains

It seems "unnecessary to say the least," as Davis long ago remarked, to postulate, as has sometimes been done, a very doubtful fracturing of anticlines owing to a supposed development of tension in them during folding, but if anticlinal belts of the initial landscape were in reality thus fissured and weakened, they would come eventually to be occupied by subsequent valleys.

Where, however, subsequent valleys have developed to some depth along anticlinal axes, leaving between them "synclinal" divides, these synclinal subsequent ridges and summits of "synclinal" mountains are, without exception, capped and protected by residual portions of resistant rock strata overlying weak formations, while other parts of the same resistant strata, which have formerly been present at a greater height than the present mountains, have been removed by erosion.[3, 4] A simplified version of this process (termed "inversion of relief" by de Martonne)[12] is presented in Fig. 94. In the succession *a–e* it is almost necessary to interpolate another stage between *c* and *d* to account for the great deepening

of the subsequent valley that takes place in *d*—a stage of destruction of relief by erosion, to be followed by general uplift; but it is conceivable that this deepening might be due to some other cause. In any actual case the erosional history is likely to be much longer and more complicated.

Synclinal divides (Fig. 94, *e*) have been a subject of remark and often a source of wonder to observers who have failed to realise the depth to which erosion has proceeded, with the removal from some

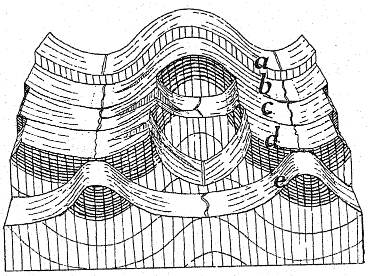

Fig. 94. Development of synclinal subsequent ridges. (From *Geomorphology*, also by the author.)

landscapes of layers of material miles in thickness. Such features are, however, not of such general occurrence throughout mountain landscapes as the attention they used to attract might seem to indicate. In any "inversion of relief" that has occurred, anticlinal divides of any anterior facies of the landscape that have been replaced in this process by anticlinal valleys are not necessarily—and probably are very rarely—consequent features; and the whole process is best regarded as merely a part of the more general one of subsequent stream development and adjustment to structure previously outlined. The phrase "inversion of topography" has been applied by Davis[7] only to cases of actual demonstrable inversion caused by the filling of valleys by lava flows, which have later become ridges, as in the case of those on the slopes of the Alban volcano, near Rome, the Meissner ridge, in Hessen, or Montagne de la Serre, in Auvergne (Fig. 326).

Resequent Forms

After a vast thickness of material has been removed by erosion during and following a succession of uplifts, the folding of rock strata formerly deeply buried, but now exposed at the surface, may be still parallel in a general way to that of the initial surface. This is, of course, unlikely to be the case except where folds are broad, open, and symmetrical, but in structures of this kind it may happen that a folded resistant stratum has such a relation to base-level that,

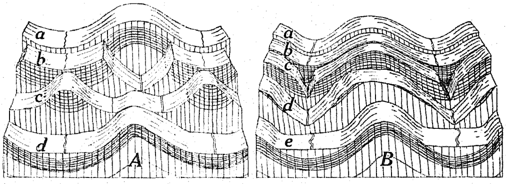

Fig. 95. A: Evolution of resequent ridge and valleys, stage *d* of diagram, developed from surface *a* through intermediate stages *b* and *c*. B: In contrast with history A, an anticlinal ridge may possibly survive as a consequent feature throughout a period of deep denudation.
(From *Geomorphology*, also by the author.)

as overlying weaker formations are eroded away, streams migrate down the dips of the resistant surface into synclinal positions, and stripped, unbroken anticlines form ridges between them. Such synclinal valleys and anticlinal ridges are unlikely to be actual survivals—throughout long-continued and deep erosion—of consequent forms, but generally must be the results of successive new adjustments to structure at successively deeper levels. They are then *resequent* (Davis)[6] (Fig. 95, A). In the mountains of Cape Province, which are formed of very ancient folded rocks, and have been exposed to erosion for a vast period, there are anticlinal ridges and synclinal valleys that are explained as resequent[8] (Fig. 96); and others are known in the Appalachian region (Fig. 97). In the mountains of south-western Iran there are enormous anticlinal ridges, but these may be consequent (Fig. 95, B) if the implied interpretation that the mountains are still undergoing erosion in their first cycle[9] can be accepted as substantially correct.

Notwithstanding the prominence given in landscape descriptions to both anticlinal and synclinal ridges, the majority of subsequent ridges in mountains of folded rocks are localised on the outcrops of

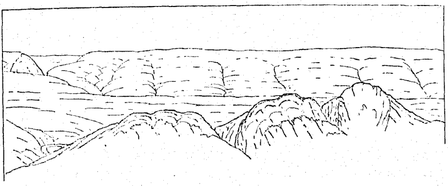

Fig. 96. Resequent anticlinal ridge (forming distant skyline) of resistant Table Mountain sandstone—the Klein Zwartberg, Cape Province. (After W. M. Davis, redrawn.)

exposed edges of inclined resistant strata. Sometimes the resistant character of a ridge-forming stratum is quite obviously in contrast with the weakness of its neighbours; but the contrast is not always so conspicuous, and stream action is able, in the course of untold

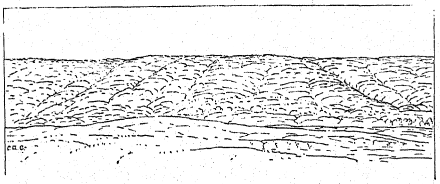

Fig. 97. Stripped anticline of hard rocks forming a ridge, believed to be resequent; Walkers Mountain, Virginia: described by F. J. Wright. (Drawn from a photograph.)

ages, to search out differences in the texture, solubility, degree of induration, closeness of jointing, and probably other properties of rocks that are not otherwise apparent.

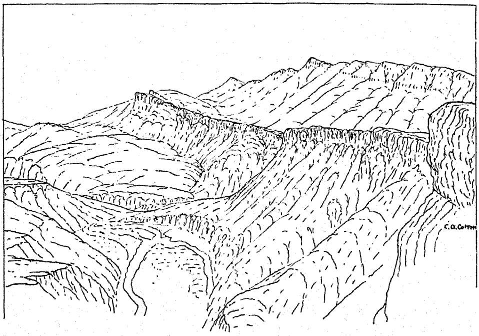

Fig. 98. Escarpments of homoclinal ridges developed on the outcrops of limestone strata, Waipara valley, Canterbury, New Zealand.

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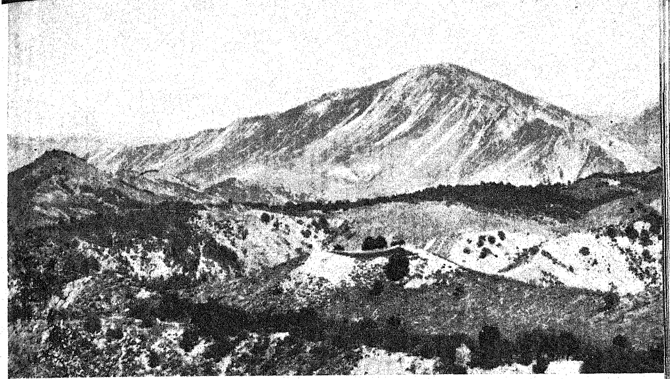

Fig. 99. Homoclinal ridge, Marlborough, New Zealand, showing contrast between escarpment (left) and dip slope (right).

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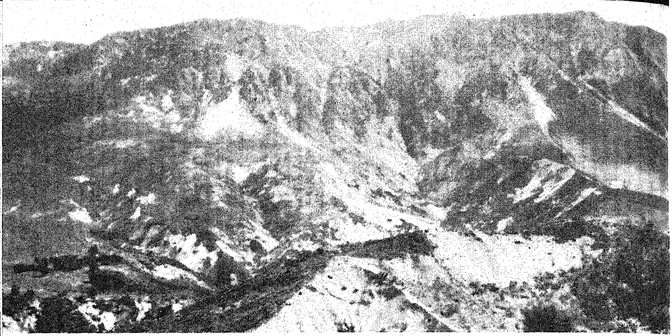


Fig. 100. Full-face view of the escarpment of the homoclinal ridge of limestone shown in Fig. 99.

CHAPTER X

Homoclinal Features and Structural Benches

BY THE TIME THAT A DISTRICT OF STRATIFIED ROCKS IS MATURELY dissected by subsequent streams the ridges and uplands forming the divides between these have generally assumed profiles determined by the arrangement of the strata (Fig. 98). In general ridges are not symmetrical, for the law of equal declivities does not apply to this case, where the rocks are not homogeneous but are contrastingly weak and resistant to erosion on opposite sides of each crestline.

HOMOCLINAL RIDGES

The resistant inclined strata now outcrop as *homoclinal ridges* (Figs. 99, 100) bounded by *escarpments* and *dip slopes*. In common language "escarpment" and "scarp" have the same meaning, any line of cliffs, or abrupt slope breaking the continuity of a surface. Economy of words and the necessity for precision in nomenclature have led to the almost invariable use of "scarp" in that sense in geomorphology, while "escarpment" is limited to the meaning here defined. It may be considered to be a contracted form of "structural escarpment".

The dip slope is the back or gentler slope of the ridge, and is determined by the inclined upper surface of the resistant ridge-maker stripped of softer overlying material and itself only very

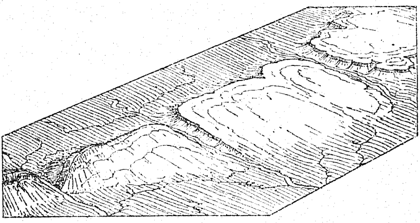


Fig. 101. Transition from a hogback (left) through a homoclinal ridge to a cuesta, and thence to a mesa (right). (After Davis.)
(From *Geomorphology,* also by the author.)

slightly eroded, though generally reduced a little in steepness, and somewhat roughened and seamed by shallow valleys cut by streams flowing on it in the direction of the dip. These are sometimes termed "resequent" without further question, a description which implies a return to the stream direction of former consequents, but the propriety of this usage is doubtful.

Fig. 102. Hogback, Maunsell's Taipo, Wellington district, New Zealand.

L. C. King, photo

Fig. 103. Escarpment, 3000 feet high, of horizontal sandstone, Table Mountain, Cape Town, South Africa.

The survival of dip-slope surfaces contrasts strongly with the depth of erosion on parallel belts of weaker rocks. Where dip slopes are very steep the contrast between these and escarpment slopes is lost, and so homoclinal ridges on steeply dipping strata grade into *hogbacks,* which are found also on outcrops of vertical ridge-makers (Figs. 101 and 102).

Structural Escarpments

Structural escarpments, such as are found forming the steep fronts of homoclinal ridges, are developed by erosion wherever outcrops of resistant strata and also those of weaker formations underlying them are exposed as belts on the surface, as they commonly are along the sides of subsequent valleys. The escarpments of homoclinal ridges, as they slope in the direction opposite to the dip of the strata, have "anti-dip", "anaclinal", or, as they are sometimes termed, "obsequent" slopes. Strictly "obsequent" means reversed in direction of slope or flow, but it has become rather well established in the sense of "anaclinal" without other implication,[2] though this usage has been criticised by Baulig.[1]

Fig. 104. A rapidly retreating escarpment of limestone at Weka Pass, Canterbury, New Zealand.

Escarpments are formed on the exposed edges of horizontal strata also. The ridge-maker, or cap rock of the escarpment, outcrops in the crestline and upper part of the face of the escarpment in some cases as a steep, and even vertical, cliff, the latter being well exemplified in the steep "krantzes" of the escarpments of horizontal strata in South Africa (Fig. 103). Below is the contrasting gentler slope on the weaker underlying rock, though this is always somewhat steepened by talus from the cap rock. With varying rock hardness, permeability, and rate of attack by erosion conditioned by climate and relief, however, the sharpness of an escarpment edge may vary from a cliff to a smoothly rounded form.

The process of development of an escarpment involves retreat of the escarpment, or a shifting towards the direction of the dip of the crestline divide at the escarpment edge—a phase of the more general process of "homoclinal shifting". The resistant rock of the escarpment is affected but little by the corrasion of anaclinal streams that arise on it until these become very steep; but on the softer material below, these streams burrow back so as to leave the edge of the cap rock badly supported, and even, it may be, overhanging, so that blocks are constantly breaking away (Fig. 104)

and falling from a retreating sharp edge, which is analogous to that of a waterfall in rocks of similar structure, but extends along the length of a linear outcrop. More or less rapid retreat is thus characteristic of escarpments, and is generally made manifest by the presence of a sheet or thin talus slope of coarse waste, which is derived from the edge of the resistant escarpment-making stratum and buries most of the outcrops of underlying rocks (Fig. 100). This mode of retreat requires the development (and persistence) in the escarpment profile of slopes that are steep above and relatively gentle below, and this is the explanation of the characteristic concavity of such profiles. The profiles of escarpments will be discussed more fully in Chapter XIV.

Hogbacks

Hogbacks on vertical and nearly vertical strata have profiles not only symmetrical but also persistently concave on each side; and, of course, they differ from homoclinal features in being fixed in position—rooted, as it were, on their ridge-makers.

Cuestas

Homoclinal ridges grade into *cuestas*,[3] which are developed on escarpment-forming strata of very gentle inclination (Fig. 101). Cuestas are necessarily broad, and present also greater contrast between escarpment and dip slopes than is found in typical homoclinal ridges. The dip slopes, indeed, are sometimes so extensive and so nearly level that they have the appearance of plains, while near escarpment crests they are regarded as plateaux—the Marne Plateau, for example, in Northern France[12] (Fig. 105).

In the direction of the dip, however, the gentle slope merges into the lowland plain, or flat subsequent-valley floor, developed by erosion on the overlying weak stratum. Such a lowland between two cuestas is commonly a geographically important landscape feature; together with the dip slope bounding it on one side and the escarpment on the other it is sometimes termed a *vale* (Fig. 106). Where subsequent features are developed during the mature dissection of a coastal plain of simple structure, they are alternating vales and cuestas parallel with the coast, making it a "belted coastal plain", exemplified by parts of the Atlantic coastal plain of North America.

Various groupings of cuestas have been recognised, such as *wide-spaced*, *close-set*, and *overlapping*,[7] which depend on variations in relative thickness of the resistant and weak formations, and on the measure of the relief.

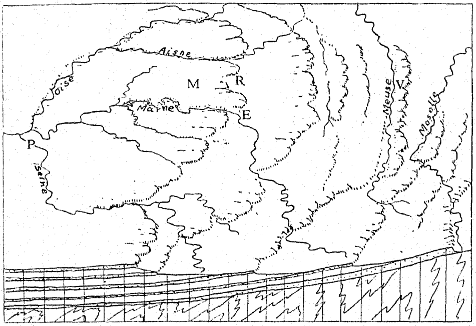


Fig. 105. Cuestas of Northern France. *E*, Epernay; *M*, Marne "plateau"; *P*, Paris; *R*, Rheims; *V*, Verdun. (From a diagram by Johnson, redrawn.)

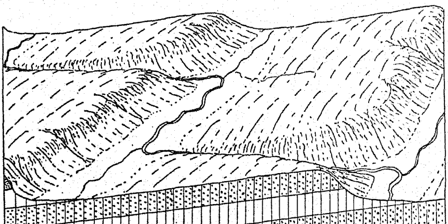


Fig. 106. Vale enclosed between linear cap-rock outcrops.

Cuestas, as well as hogbacks and homoclinal ridges, are crossed here and there by transverse streams. As these pass through hard-rock outcrops, they remain relatively young when subsequent valleys

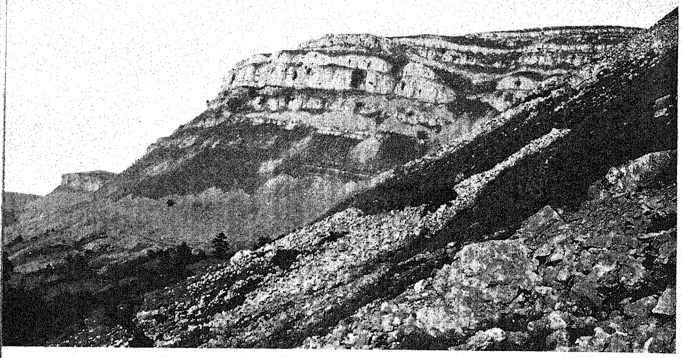


Photo from H.M. Geol. Surv. of Great Britain

Fig. 107. Scalloped escarpment of the Carboniferous limestone in Denbighshire.

are already widely opened, and on the steep sides of their gorges bare-rock outcrops are exposed, which reveal the succession and dips of strata, making clear the relations between the surface forms of subsequent landscape features and the structure of the underlying rocks. Even anaclinal streams that join the subsequents as tributaries may cut somewhat deeply into the escarpments, especially where cuestas are widely spaced. Their headward erosion embays a cuesta, so that its crestline becomes sinuous and its escarpment no longer a straight line of cliffs but "scalloped" (Fig. 107); and the sinuosity may increase as long as these small streams are still deepening their valleys. Later, however, when anaclinal, as well as through transverse, valleys are so deeply cut that development of embayments along the former has ceased, salients between them continue to be worn back as escarpments of diminishing height, so that a fading escarpment in a late-mature landscape becomes more and more nearly straight.[15]

Bevelled Cuestas

Bevelled cuestas (Fig. 108) are developed in a youthful stage of dissection of a peneplain beneath the surface of which are gently inclined strata. Cuestas of a former cycle (A) have long ago been worn down by prolonged erosion (B), and a remnant of the peneplain that was the initial form of the current cycle bevels the present-day cuesta (C). In the case of a cycle introduced by uplift

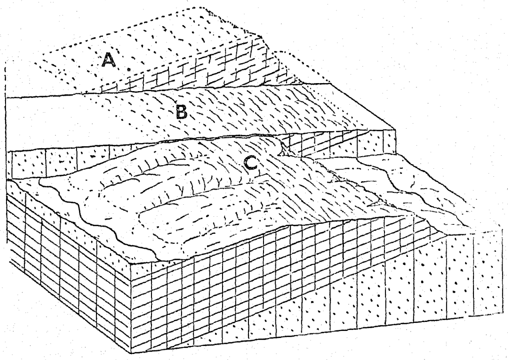


Fig. 108. Development of a bevelled cuesta.

of very moderate measure (as in Fig. 108) the bevelled cuesta is a stable form, and, though strictly it is a youthful element of the landscape, its destruction is delayed until late in the cycle, when forms of full or late maturity will replace it. The best-known two-cycle or bevelled cuestas are those of eastern and south-eastern England,[14] recognised by Davis.[3, 6] The cuesta-making strata are here the limestones of the Mesozoic sequence, and vales are developed on the broad outcrops of the weaker strata.

Homoclinal Shifting

The process of *homoclinal shifting*[9] affects not only all retreating escarpments, in the case of which migration of crestline divides is obviously taking place, but also—in the case of progressive deep dissection resulting from progressive or continuous uplift—all parallel lines and belts of subsequent origin in the landscape. Under these conditions vales and cuestas—or subsequent valleys and homoclinal ridges—must migrate, or creep, laterally in the direction of the dip of the strata (Fig. 109). Obviously the extent of such

migration is greatest (other things being equal) in the case of very gently dipping structures.

Zigzag courses of streams, the general trend of which is diagonally across the strike, may in some cases be ascribed to homoclinal shifting.[9] The river may be straight at first (being possibly super-

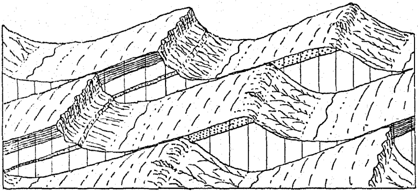


Fig. 109. Homoclinal shifting. Three successive profiles developing during progressive erosion.

posed), but by the time the surface is dissected into homoclinal ridges the course has become zigzag (Fig. 110, B), as those parts that cross weak-rock outcrops have migrated down dip slopes until they have become longitudinal; and these are connected by transverse reaches crossing the outcrops of the resistant beds by the

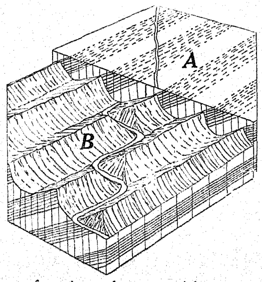


Fig. 110. Development of a zigzag from a straight river course by homoclinal shifting.
(From *Geomorphology,* also by the author.)

shortest paths. Such courses, with many right-angle bends, are common, but all have not necessarily been developed in the same way. The joining-up of successively captured transverse streams by reaches of subsequent origin produces a similar result (Figs. 83, 106).

Mesas and Buttes

Mesas and *buttes** are features closely related structurally to homoclinal ridges, though subsequent streams are not generally

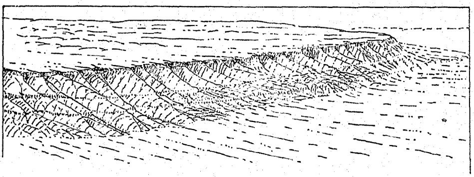
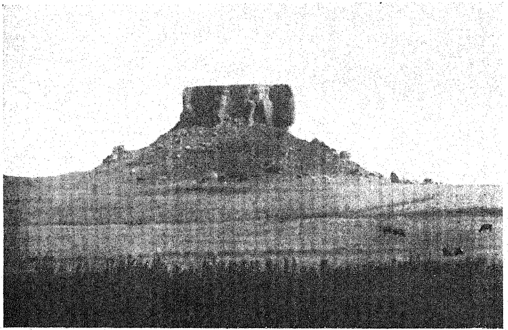


Fig. 111. Escarpment of a mesa, Rock Springs, Wyoming. (Drawn from a photograph.)

responsible for their isolation. They are salient features capped by large or small remnants of resistant horizontal strata overlying weaker material, and are bounded on all sides by escarpments. Large table-like forms are mesas (Figs. 101, 111) and small residuals are buttes (Fig. 112). The length and breadth of a butte are, at most, not much greater than the height; but a mesa may be many square miles in extent, its surface being a structural plateau. Mesas are cut up by dissection and further reduced in size by retreat of the escarpments that bound them, for erosion on these is rapid owing to weakness of the materials underlying the lower slopes, though steepness is maintained owing to the resistance offered by the capping formation. Thus mesas are reduced in the course of time to buttes, and later disappear.

Mesas are particularly well developed where horizontal sheets of lava lie over weak materials and the more or less dissected margins of the lava retreat as escarpments. Some mesas are remnants of blocks of country (consisting of horizontal strata) that have

* Pronounced *may-sa* and *bewt*.



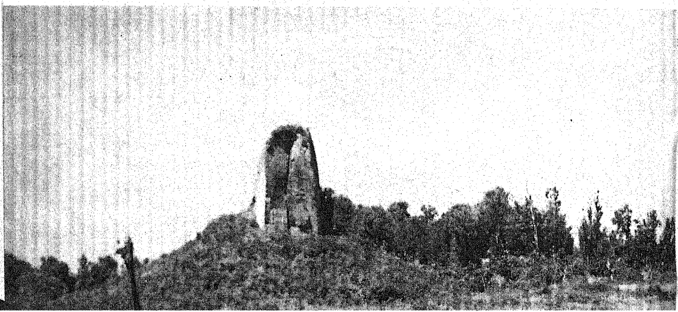
L. C. King, photo

Fig. 112. Butte near Ficksburg, Orange Free State, South Africa.

been uplifted between faults; the escarpments around these have retreated far from the original fault boundaries of the blocks. Even differential depression of a block of a resistant stratum bounded by faults may preserve it from destruction for so long that the erosional lowering of the land surface at some future time may leave it standing as a mesa, just as resistant rocks downfolded as synclines

Fig. 113. Ignimbrite butte at Mamaku, New Zealand, perhaps a subsequent form.

Professor J. A. Bartrum, photo



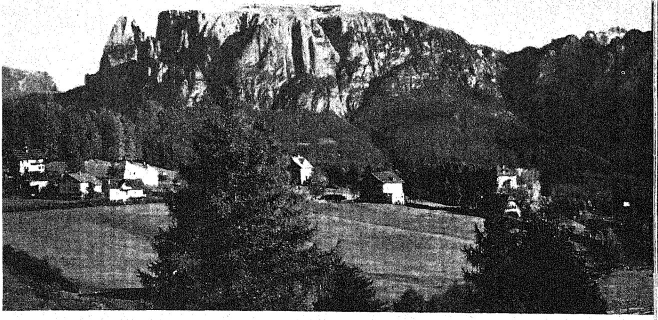


Fig. 114. The Schlern mesa, of dolomite, South Tyrol.

may later become mountain crests. Table Mountain (Fig. 103), at Cape Town, South Africa, seems to be the result of such survival after a long erosional history (See Chapter XXII). Higher-standing surrounding parts of the same resistant stratum were destroyed by erosion in an age long past.

Buttes and Mesas of Subsequent Origin

In some cases, though quite exceptionally, buttes and mesas are subsequent structural features; but this is only in so far as they survive at places where certain portions of rock sheets are more resistant to erosion than the average material. Of this nature are the conical "tepee butes" of Colorado,[10] each held up by a tentpole-like vertical column of shelly limestone enclosed in softer shale. The core rocks of some subsequent buttes termed "klints" were formed as small coral reefs, or reef knolls, in the Silurian period at a time when, to quote Cumings and Schrock, "the reef mounds must have been crowded in the Niagaran sea like the coral islets behind the Great Barrier of Australia". The klints of the island of Gotland, where the name originated,[11] consist of compact and resistant limestone; those of Indiana and adjacent states are dolomite. Some features of the ignimbrite, or so-called welded tuff, plateau of the North Island of New Zealand must be classed as subsequent, and these may include a group of remarkable pillar-like buttes at

Mamaku. These possibly mark points at which semi-coherent material became more completely indurated around fumaroles (Fig. 113).

Differential erosion has exposed fossil atolls that were built in a Triassic sea as the dolomite mesas of South Tyrol (Fig. 114), and these must, therefore, be classed also as subsequent forms.

Structural Plateaux

Related in form and structure to mesas are *stripped structural plateaux*, or simply *structural plateaux* (Fig. 115), which develop on horizontal strata if relatively very weak materials are stripped away

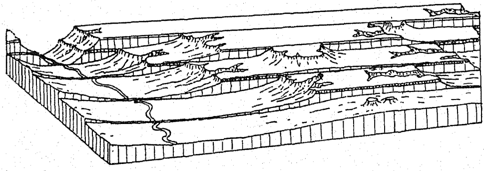
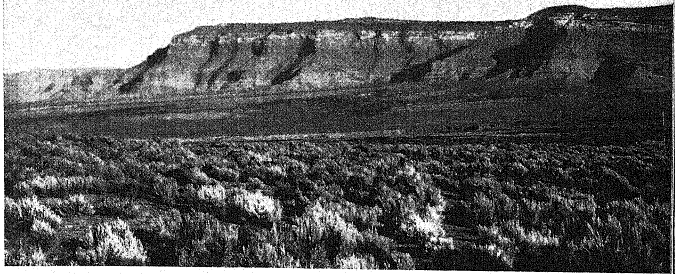


Fig. 115. Dissection and destruction of a structural plateau, with accompanying development and progressive destruction of benches and mesas. (After a diagram by Davis, redrawn.)

(From *Geomorphology*, also by the author.)

by erosion so as to expose the structural surface of a resistant stratum. Such features occur widely in Africa and are of broad extent in the down-stepping series of the Colorado plateaux, in the south-western United States (Fig. 116). In these regions semi-aridity may delay the destruction of a structural plateau by escarpment retreat and marginal dissection. In the limestone structural plateau of the south of France, and elsewhere in southern Europe, development of swallow-holes and underground drainage channels due to the solubility of the rock prevents the formation of surface streams and so delays normal dissection of the surface. Even without special retardation of erosion, however, the dissection of structural plateaux on *thick* resistant strata is a slow process, and so they are stable, or long-lived.

The development of a featureless plateau by complete, or nearly complete, removal of overlying weak material is controlled by the



Professor Douglas Johnson, photo

Fig. 116. The Vermilion Cliffs escarpment, which separates broad structural benches in the Colorado Plateau province of western North America.

level of the surface of the resistant plateau-making layer in very much the same way as the lowering of the general land surface to a peneplain is controlled by the general base-level. The edge of the hard stratum is wasting away as an escarpment, and where streams cross the edge its level is for them in a certain sense a local base-level.

It has been questioned with regard to structural plateaux whether a great area of a level resistant stratum can be cleanly stripped of its cover unless it lies low in relation to the general base-level.[8] At a high level it may emerge only as a bench, which will be progressively destroyed (Fig. 115). If, however, a structural plateau was close to the general base-level when it was stripped, the land surface that was developed in the stripping process was to all intents and purposes a peneplain (Chapter XVI). That part of the great Australian peneplain is a case in point where, in the Blue Mountains of eastern New South Wales, it coincides over a large area with the stripped surface of the resistant Hawkesbury sandstone of Triassic age (Fig. 117).

Whether stripped at a high elevation, as perhaps sometimes occurs, or uplifted after stripping, a structural plateau is subject to dissection with the development of highly characteristic forms.

As dissection proceeds, streams, some of them consequent, some perhaps antecedent, but many also insequent, cut valleys that may be deep and very steep-sided, being bounded by escarpments (Figs.

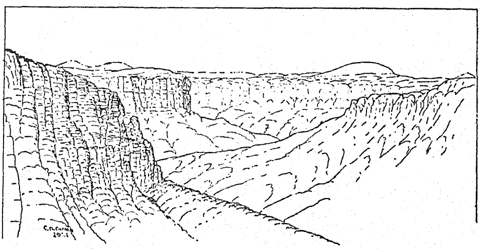
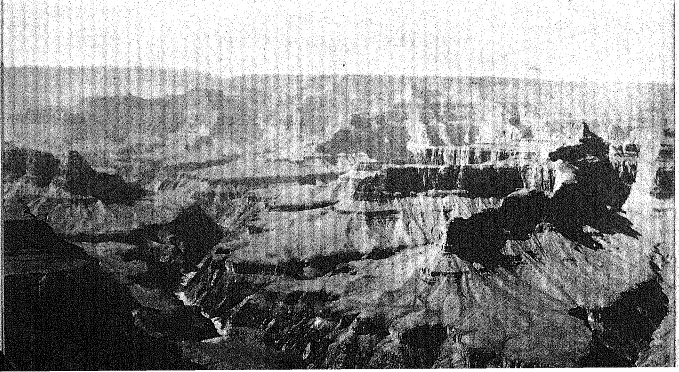


Fig. 117. The valley of the Grose, Blue Mountains, New South Wales. The Blue Mountains plateau is the upper surface of the resistant Hawkesbury sandstone, and is in course of destruction by the opening out of valleys, the sides and heads of which are escarpment cliffs that are in most places unscalable.

Fig. 118. Structural terraces and dissected valley-side spurs projecting into the Grand Canyon of the Colorado River, Arizona.

Professor Douglas Johnson, photo



117, 118). These valleys separate jutting points and peninsulas of the structural plateau (Fig. 115), and later isolate portions of it as mesas and buttes. Finally all these are consumed, having wasted away at their margins by the process of escarpment retreat.

Structural Benches and Terraces

In the course of a single cycle on horizontally bedded formations, similar structural features may reappear more than once if there are successive resistant strata to be exposed by erosion. Lower plateaux begin to emerge as fringing step-like *structural benches* (Fig. 115) long before the highest plateau is destroyed or even more than marginally dissected. Structural benches bordering a valley are broad or narrow mainly in response to variation in the pattern of weak and resistant, thick and thin strata; for, other things being equal, the escarpment at the outcrop of a thick resistant layer will retreat slowly, and that of a thin layer more rapidly; and each bench is constantly being narrowed by retreat of its own marginal escarpment, though at the same time being extended in width as that above it recedes. Depth, or juvenility, of a valley below also speeds up escarpment retreat, and this retreat sharpens the edges. The high

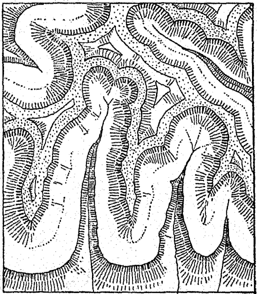


Fig. 118A. Dissection by amphitheatre-headed valleys scallops the highest escarpment flanking the Grand Canyon of the Colorado; but more concentrated (linear) erosion cuts V-shaped ravines in a lower escarpment. (After W. M. Davis.)

escarpments of the Colorado plateaux where they are most freshened and steepened thus by rapid erosion at the base crumble back at such a rate that they are fringed by vast landslides[4] though elsewhere their retreat is slower and more orderly (Fig. 116).

The longitudinal profiles of the streams dissecting plateau benches long remain ungraded, being broken by falls and rapids where they descend over the outcrops of resistant layers. In these steep descents the streams are confined in narrow gorges, or canyons, but such valleys open out widely where streams flow over weak-rock outcrops as they cross broad plateau benches. The side slopes of young canyons deeply cut in a succession of weak and resistant horizontal beds are characteristically broken by narrow structural benches, or *structural terraces,* and their escarpments (Fig. 118). Amphitheatre-headed embayments in such escarpments develop as the back wall retreats at places where little concentrated drainage enters the heads of small side-branch streams (Fig. 118A).[4, 13] Where, on the other hand, such streams are well-defined and of greater volume, they cut back in narrow-headed ravines into the bench or plateau above.

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CHAPTER XI

Transverse Valleys; Superposed and Antecedent Gorges

THE ORIGIN OF THE VALLEYS, OR PARTS OF VALLEYS, BY WAY OF WHICH transverse reaches of the rivers in a trellised pattern break through strike ridges and anticlinal divides has given rise to much discussion, the outcome of which is that it has become obvious that no single explanation of such transverse courses can be given. Some may be ancient consequents inherited from a first cycle, in which their positions were determined by the transverse synclinal folds of an irregularly folded or warped initial surface. Some others, though these are no doubt exceptional, are to be regarded as being as truly subsequent as the parallel streams aligned with the strike of the stratified rocks, having been developed by headward erosion along transverse or diagonal belts of crushed rock. Others, again, may be consequents of a later cycle that has been introduced by upheaval of a well-developed peneplain accompanied by warping or tilting strong enough to establish streams in entirely new courses, thus causing the abandonment or partial abandonment of former courses adjusted to the structure. Some transverse reaches may possibly result from inheritance of courses diverted by abstraction in a former cycle which reached an advanced stage of senility; in that condition departures from former adjustment may have been brought about by the development of wide valley floors cut by lateral stream corrasion across the reduced relief features on the resistant formations when these have been weakened by deep weathering. A great many transverse reaches are certainly, however, remnants of formerly more continuous transverse and diagonal courses superposed on the landscape from unconformable covering strata that have long since been entirely removed from the surface by erosion either in the present or in a former cycle, though such valleys may have been broken into short lengths and largely replaced in the drainage systems by subsequents developed on the underlying structures.

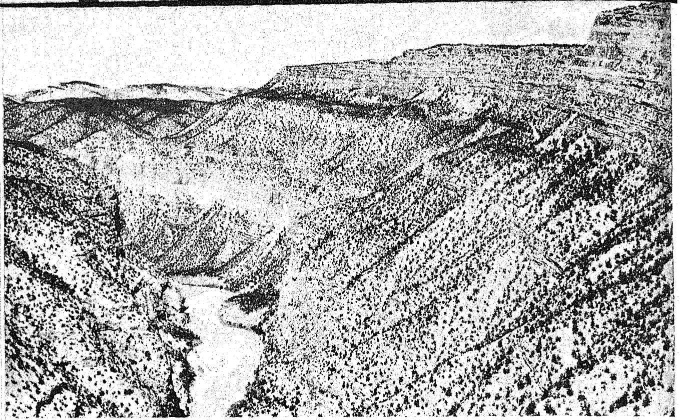
Transverse Gorges

Most of the foregoing explanations of short transverse reaches may be applied also to some or other of the great gorges by way of which many large rivers make their way through mountain ranges. If such gorges were blocked, so that the rivers were compelled to abandon them, other spillways would generally be available, perhaps somewhat longer and more roundabout, but broadly open and unobstructed, through which the rivers could take easy courses as consequents around the mountain barriers. It is obvious, therefore, that when the rivers took the courses in which they have entrenched themselves in their present deep gorges through the mountains the apparently easier ways around the ranges were not open to them; these, together with the ranges, are of more modern development than the *initiation* of the transverse courses.

Superposed and *antecedent* origins of transverse gorges are possible, but in many cases there is doubt as to which is the correct explanation; while a third hypothesis has also to be considered, namely, that of headward erosion, put forward as a competitor of the hypothesis of antecedent origin to explain great transverse gorges.[14] Though headward development of subsequents on crushed zones is quite probably the correct explanation of some minor transverse gorges, there is no evidence or probability of such guidance in the development of great gorges through mountain ranges, and without it there is little to be said in favour of the hypothesis of headward erosion.

Antecedent Gorges

The origin of superposed consequent courses has been touched upon in an earlier chapter, and the theory of antecedent rivers may now be outlined. Where uniform or nearly uniform uplift at the initiation of a cycle results in inheritance of a complete pattern of streams ("antecedent" in the broadest use of that term) from an ancient land surface into the infancy of the new cycle, such streams must take their chance of survival in a struggle with vigorous competitors, and in most cases they are likely soon to lose their distinctive character. There is a possibility, however, of some short transverse portions of river courses having had this origin.



Geo. A. Grant, photo

Fig. 119. Lodore Canyon of the Green River, originally selected as type of an antecedent gorge, but now interpreted as superposed.

Large rivers of strong slope, well inclosed in steep-sided valleys, or, in other words, vigorous adolescent rivers, have the best opportunity to persist across a belt of rising or writhing country, because a great deformation would be required to throw them from their courses. Small streams or large ones of faint slope in an open low country are more easily deflected. (Davis.)

In the true antecedent type "the essence of the antecedent relationship is a successful contest waged by rivers against *localised* uplift" (Wooldridge and Morgan). It was in this sense that antecedent rivers were recognised (and so named) by Powell,[18] who had in mind the probability that some "rivers have held their courses through mountain ridges that slowly rose across their path; the rivers concentrating the drainage of a large headwater region upon a narrow line, cut down their channels as the land was raised" (Davis). As Powell himself very forcefully expressed it: "The river had the right of way. . . . It was running ere the mountains were formed. . . . The river was the saw which cut the mountains in two."[18] Though the course of the Green River through the Uinta Mountains (Fig. 119), for the explanation of which Powell conjured up the antecedent type, is now regarded as a case mainly of superposition,[2] the idea of antecedence seems to be valid in its application

to many other gorges. Davis has suggested as better examples, "the Rhine below Bingen (Fig. 215), the Meuse in the Ardennes, or several of the Himalayan rivers in the gorges that they have cut through the youngest marginal ridges of the range". The antecedent nature of the last named (and of the Sutlej in particular) was recognised and remarked upon, indeed, long before Powell had given such rivers a name.[16] One might add the Danube at the Iron Gate,[8] and the lower gorge of the Isker. The course of the Meuse through the Ardennes is alternatively explained as superposed,[4] and such is now held to be the correct explanation of various supposed examples of antecedent gorges in the Rocky Mountain region,[2] but the place of these is taken by innumerable other examples in warped and faulted regions, notably those in which a surface far advanced towards senility, either bare or with shallow cover only, has been deformed and upheaved. Andrews[1] insists that the world is dotted over with such antecedent gorges. Notable examples he cites in Australia are those of the Snowy, Hawkesbury, Clarence, and Brisbane Rivers. Lawson's interpretation of the history of the Nile makes it also antecedent.[13]

A New Zealand example of a truly antecedent gorge is that of the Waiau River (Frontispiece) upstream from the recently depressed and alluviated Culverden basin plain (Fig. 123). This gorge has been cut during tilting upheaval of a block bounded on the north by a growing fault scarp, which is notched by the south-flowing river.[7a] During intermittent movement, which will probably continue, terraces have been cut in the gorge and progressively tilted by the upheaval.

Air gaps in the crestlines of recently uplifted ranges, especially in the case of smaller examples, may remain as evidence that rivers have for a time persisted in their courses across the uplift, but later have been *defeated* and turned aside into new courses. There is a deserted valley of this kind across one of the fault-block ridges of southern Oregon[11] (Fig. 120). Where large rivers have persisted in antecedent gorges it must generally be assumed that many smaller and less vigorous rivers that are unable to cut down their channels as fast as the land rises have been ponded and turned aside into new consequent courses. Many streams so defeated must become tributary to their more vigorous neighbours, which, thus reinforced, are the better able to maintain their antecedent courses in spite of further uplift.

There are in New Zealand a number of rivers which have the appearance of antecedents in that they make their way in gorges through ranges that have recently been uplifted, mainly as fault-bounded tilted blocks, around the ends of which there were, apparently, during and immediately after the earth movements, comparatively low tectonic gaps, and through these gaps consequent drainage would have spilled if the uplifts had taken place very rapidly, or if there had been no rivers in existence in the region prior to the deformation. It thus seems that the rivers are antecedent to at least the greater part of the uplift of the ranges that they cross, but it is not definitely known whether they took their present courses in a phase of emergence without notable deformation possibly preceding the great deformation (the "Kaikoura" earth movements, of very late Tertiary date, correlated by Andrews with the Kosciusko uplifts in Australia) to which the present-day major relief features owe their origin, or whether they were guided by the first wrinkles of the surface as it emerged from the sea, and have maintained the consequent courses then assumed during a continuation of the movements, although in the later and more intense paroxysm the shape of the surface and the pattern of mountain blocks changed considerably, so that what are now relatively low gaps in the tectonic framework do not necessarily coincide in position with the earliest-formed wrinkles on the writhing surface.

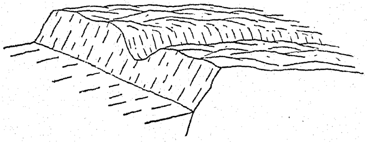


Fig. 120. Deserted antecedent gorge in an uplifted lava block south of Fort Klamath, Oregon. (After Douglas Johnson.)

Anteconsequent Gorges

An explanation of the through-going gorges may be found by making either of the foregoing assumptions, but it may be said in

favour of accepting the latter one that some at least of the great water gaps seem to have consequent relationship to tectonic gaps or crestline sags in the framework. This is a type of river course recognised by Davis in the mountains east of the Adriatic Sea as "consequent on some early stage of the warping and antecedent to the rest".[9] It has been suggested that such courses should be placed in a special *anteconsequent* class.[5] The importance of making a distinction, where possible, between true, or typical, antecedent rivers and the anteconsequent variety is related to the fact that the former are two-cycle and the latter one-cycle features; but unless it is thought necessary to emphasise this distinction, which is of more geological than geographical importance, anteconsequent may be classed with antecedent courses, of which they may be considered to be a variety.

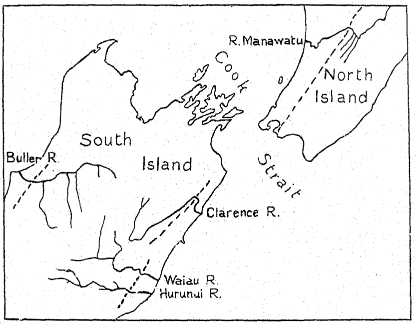


Fig. 121. Sketch-map, showing the positions of the Manawatu, Buller, Clarence, Waiau, and Hurunui gorges.
(From *Geomorphology,* also by the author.)

Among the New Zealand rivers of possibly anteconsequent, or doubtfully antecedent, origin conspicuous examples on a large scale are the Manawatu River (Fig. 121), in the North Island, which leads the drainage from a large area on the eastern side of the island to the western coast by way of a gorge cut at a low sag in the main dividing range; the Buller, in western Nelson (Fig. 121); the Lower Clarence gorge, which provides an outlet through the

V. C. Browne, photo

Fig. 122. View looking up the transverse gorge (3000 feet deep) of the Lower Clarence, which cuts off the Sawtooth Range from the north-eastern end of the Seaward Kaikoura upheaved block. (Compare Fig. 121.)

Seaward Kaikoura—Sawtooth Range for the consequent drainage of the great tectonic depression of the Middle Clarence Valley (Figs. 121, 122); and the twin outlets from the Culverden Plain. In the last-mentioned example the Waiau and Hurunui Rivers (Figs. 121, 123) have cut gorges 2000 feet deep through an uplifted block of country, either of which would suffice to drain the area, while

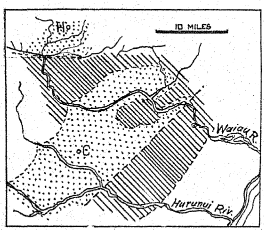


Fig. 123. Antecedent and possibly anteconsequent gorges and gravel-filled tectonic basins in North Canterbury, New Zealand. Lined areas are uplifted blocks crossed by gorges; stippled areas are gravel-filled basins; *C*, Culverden.

if neither were present an easy outlet is now open to the south. Small-scale examples of courses that are possibly anteconsequent are also very common in New Zealand, especially in the South Island, but an alternative hypothesis of superposition has to be considered in most cases—and must not, indeed, be lightly dismissed when larger through-going gorges are under investigation. In the case of the Manawatu the river is, indeed, superposed at the gorge on old rocks present as a core under an anticlinal structure of a Pliocene cover. Apart from the superposition the whole course of this river (with those of its tributaries) has been alternatively explained as simply consequent,[17] a hypothesis that implies, if relied on altogether, a vast amount of differential erosion, much of it post-Pliocene, to explain very extensive lowlands traversed by

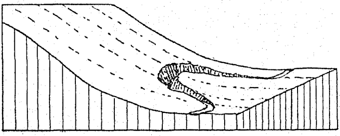


Fig. 124. Diagram of the Nepean gorge.

these rivers above the gorge. The fact that differential earth movements are still in progress in adjacent districts, however, makes admissible the auxiliary hypothesis that some local upheaval of the range through which the gorge passes has taken place since the consequent course was assumed.

The Nepean gorge, in New South Wales, is clearly anteconsequent, though of an unusual variety. Where the peneplain that is arched up over the Blue Mountains is bent in a strong monoclinal flexure along the eastern flank of the arch, a trough developing parallel to this flank has guided the Nepean River in a consequent course; but it appears that the river, taking a westward swing on the floor of its open valley before the monoclinal uplift ceased, became incised on the slope (Fig. 124). Perhaps the Blue Mountains arch expanded eastward during the last stage of its uplift. "The result is remarkable, since the river, after flowing over

a broad valley, suddenly enters a gorge at the base of the monocline and then emerges on to its original plain once more".[3]

Gorges of Superposed Rivers

In the case of gorges through mountain ranges that are of *superposed* origin, in contrast with antecedent gorges the range through which the gorge has been cut, instead of rising during the gorge-cutting, was in existence with full relief prior to the commencement of the incision of the river valley across it, being, however, temporarily buried beneath a cover of essentially weak material when the river took its present course at a higher level over the surface of this cover. Many gorges that have been supposed to be antecedent have afterwards been shown to be superposed, and the same fate may await others. In a number of cases that have been carefully examined the decision between the two possible explanations remains in doubt, failing the discovery of decisive evidence in favour of either.

Land surfaces of strong relief developed in long-past ages have been extensively buried beneath thick deposits of relatively weak covering strata of river-laid or other terrestrial origin, and in the course of modern erosion such surfaces may be stripped of their cover and emerge again in more or less altered forms but retaining most of the relief they had before burial. Many courses, however, generally consequent, taken by rivers over the covering layers have been superposed on the undermass in such a way as to cross ridges, hills, or mountains of its surface in water gaps that have been incised as gorges simultaneously with the resurrection of the salient forms they traverse. The Clifton Gorge of the Avon, near Bristol, is explained in this way; and burial of spurs during a Pleistocene phase of aggradation, followed by development of a widely meandering course and superposition of this on the buried spurs, explains the gorges of the lower Severn valley.[19]

In some cases the buried hills or ridges have not yet re-emerged, but rivers cutting deep valleys through their own alluvial deposits are superposed in gorges through ridges or valley-side spurs of hard rock that they have formerly buried. Such is the explanation of the gorges of the Rakaia and Waimakariri, which are constrictions of otherwise broadly incised courses across the great alluvial plain of Canterbury, New Zealand (Figs. 125, 201).

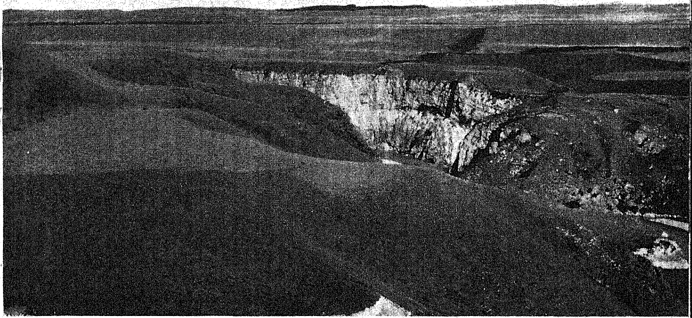
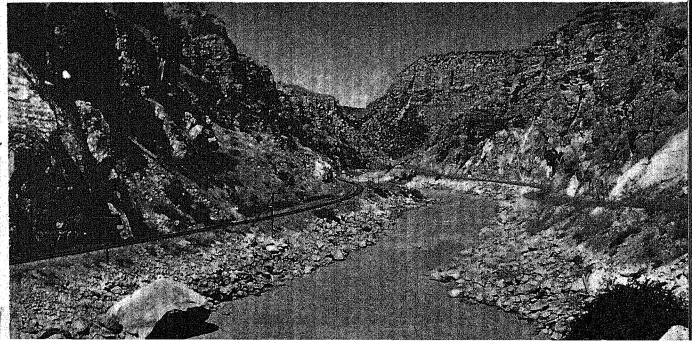


Fig. 125. Superposed gorge of the Rakaia, in hard rock revealed by trenching of the gravel-built Canterbury Plain, New Zealand.

Superposition on a grand scale is now invoked to explain most of the great gorges by way of which rivers break through various ranges of the Rocky Mountains, though antecedence is not entirely rejected as a partial explanation of some of them.[2] Rivers, such as the North Platte, Wind River (Fig. 126), and various tributaries

Fig. 126. The Wind River Canyon, a superposed gorge of the Colorado system. *Harold S. Palmer, photo*



of the Colorado, including the Green River (Fig. 119), had taken courses over deep alluvial deposits of Tertiary age that had filled tectonic basins and partially buried the mountain ranges between them, and later deepening of such courses has led to superposition on the old rocks of the ranges, which have emerged with some-

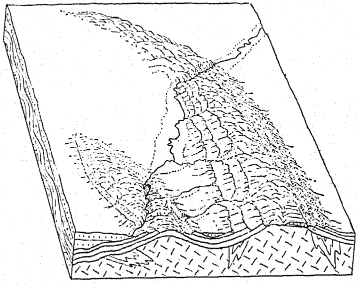


Fig. 127. Gorges of the Big Horn River, superposed from a former cover of weak superficial deposits, surviving parts of which are stippled in the front section. (After a diagram by Atwood and Atwood.)

thing very like their former relief, though now crossed by deeply cut young gorges (Figs. 127-130).

An explanation by superposition may solve the apparent mystery of a river that crosses in a gorge the low end of a range instead of

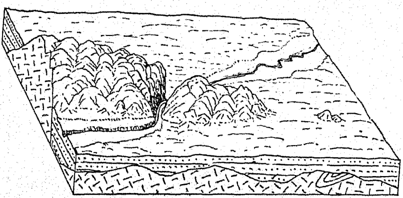
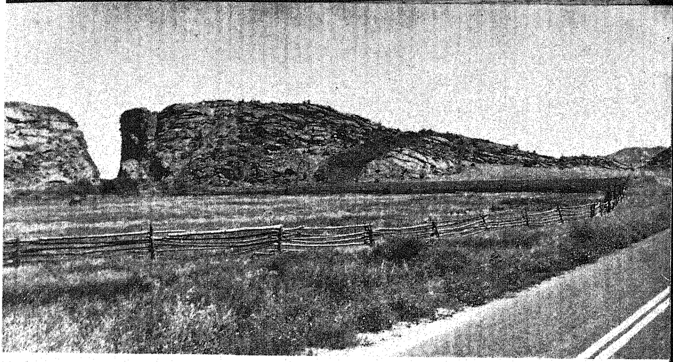


Fig. 128. Devil's Gate, Sweetwater River, Rocky Mountains. (After a diagram by Atwood and Atwood, redrawn.)



Harold S. Palmer, photo

Fig. 129. The superposed gorge at the Devil's Gate, Sweetwater River, Rocky Mountains.

taking a near-by "easy" way around it (Figs. 128, 129), or for no apparent reason makes a detour in a winding gorge among mountains instead of following a straighter course along an open lowland in weak rocks. Attention must be focused on the fact that, if superposition is the correct explanation, the "easy" ways were not available when the streams took their courses, but have been subsequently opened up by "denudation", i.e. removal by weathering, creep, surface wash, and erosion by minor streams of the weak materials in the intermont areas down nearly to local base-level, which, however, is still controlled by the major river in spite of its having become confined in a narrow gorge through the hard-rock mountains and being still engaged in laboriously enlarging its valley therein by the process of corrasion.

In another type of structure that may lead to the development of transverse gorges by superposition, there are hard cores in anticlines or upheaved blocks beneath weaker conformable cover. The deep-seated resistant cores may escape exposure at the surface during a first cycle in which a peneplain is developed, or, with deeper erosion, their higher parts may be exposed and planed off very thoroughly. In a new cycle the courses of consequent streams may cross these cores in any direction and be superposed on them as dissection proceeds. Even partial or local planation resulting from

Geo. A. Grant, photo

Fig. 130. Black Canyon of the Gunnison, a river superposed on a peneplain in the Rocky Mountains. (After Atwood and Atwood.[2])

lateral stream corrasion developing wide valleys in an incomplete cycle (Chapter XII) may result in superposition of parts of rivers on such structures, especially on low ends of pitching anticlines and upheaved blocks. Some of the smaller transverse gorges in the South Island of New Zealand, referred to on an earlier page as doubtfully anteconsequent, may perhaps be correctly explained by superposition of this kind.

Even in a first cycle, or at any rate without intercalation of a cycle of complete planation, a core of resistant rocks may have consequent rivers superposed on it. This seems to be the correct explanation of a remarkable example in the Haldon Hills, New Zealand, where a number of small streams have maintained gorges side by side when superposed on an anticlinal core of hard rock exposed by removal of a weak cover (Fig. 276).[7]

In a deformed region of compound structure it may be that some recently upheaved, first-cycle ranges have arisen on the sites of persistent structural "highs" in the tectonic framework, which are thinly covered and which are separated from one another by deeply filled local geosynclinal troughs, as is the case in California and

in New Zealand[14a]; and it may be necessary to class major gorges through these ranges as in part superposed. Even if strictly antecendent or anteconsequent in origin they will closely resemble superposed gorges.

Superposed Origin of Some Water Gaps

Mere superposition of stream patterns may often be assumed to have taken place in order to account for apparent anomalies in drainage systems of modern landscapes; and this does not imply or require any resurrection of buried mountains, or, necessarily, the

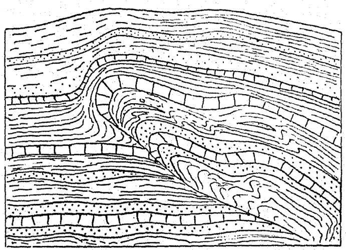


Fig. 131. A series of strata much more strongly folded at depth than at and near the surface. (After a diagram by de Martonne.)

development of new mountains by differential erosion. Notable examples of superposed consequent rivers have been mentioned in Chapter VI. In the development of the rivers there cited there can be little doubt that superposition from an *unconformable* cover has occurred on a large scale. For the explanation of some water gaps through strike ridges it is possible, however, to formulate a hypothesis of superposition of consequents from *conformable* overlying formations taking place as erosion exposes deeper-lying folded strata of a series whose upper members have escaped strong plication (Fig. 131). This is a possibly correct explanation of the water gaps, for example, in a prominent homoclinal ridge of limestone in the Clarence lowland, between the Kaikoura and Seaward

Kaikoura Ranges of New Zealand (Fig. 132), where very deep erosion has undoubtedly taken place. Superposition of some kind must here be assumed of streams that had their origin as consequents on the steep face of the Kaikoura Mountains, a range which

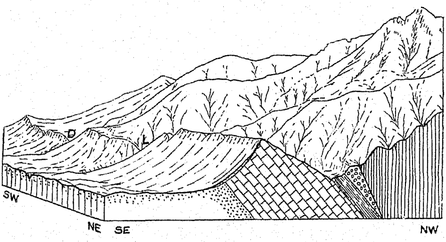


Fig. 132. Water gaps, D and L, of superposed origin in a homoclinal ridge parallel with the front of the Kaikoura Mountains, New Zealand.
(From *Geomorphology*, also by the author.)

came into existence as a result of upthrusting along a reverse fault (Fig. 132) contemporaneously with the tilting of the limestone homocline. A notable piece of evidence favouring some theory of superposition is the peculiar branching of some of the streams, which takes place upon the outcrop of the thick limestone stratum,

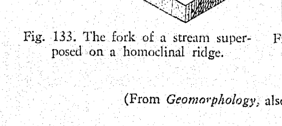


Fig. 133. The fork of a stream superposed on a homoclinal ridge.

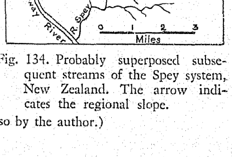


Fig. 134. Probably superposed subsequent streams of the Spey system, New Zealand. The arrow indicates the regional slope.

(From *Geomorphology*, also by the author.)

so as to isolate island-like hills of it between the branches, a phenomenon that seems to result from some cause other than headward erosion (Fig. 133). In this instance an alternative explanation that has an equal, if not greater, chance of being the correct one is

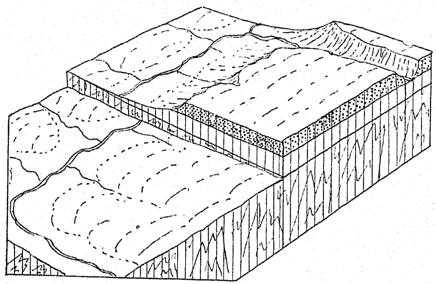


Fig. 135. Superposition of a subsequent river on an undermass.

found in a hypothesis of simple superposition from an unconformable cover of alluvial fans that probably fringed the mountain front in an early stage of its dissection (compare Fig. 276).*

Superposed Subsequents

Not only consequent but subsequent rivers also may be in certain cases superposed from an unconformable cover on to an undermass of alien structure (Figs. 134, 135). Superposed subsequents may be looked for especially where coastal-plain formations on which belted features have been developed are stripped away from the floor of older rocks on which they were deposited. A superposed subsequent origin has been suggested for streams of the Spey system, tributary to the Conway River, New Zealand.[6] Their relation to the south-westerly strike of covering strata preserved near at hand, which were formerly more widespread, is shown in Fig. 134.

* A somewhat similar explanation of the transverse course of the Medina, in the Isle of Wight, has been given by E. B. Bailey (Tectonics and Erosion, *Jour. Geomorph.*, 2, pp. 116-120, 1939).

Broadly opened gaps, now abandoned by the large river that cut them, through the Watchung Ridges, of New Jersey, have been explained as parts of a former valley of the Hudson River occupied at a stage of its history when it had been superposed on these undermass ridge-makers from a subsequent course it had followed in a vale on a belted mature surface of a coastal-plain cover.[12]

A likely place for superposition of a subsequent river course is a vale that lies between an undermass exposed by erosion on the one hand and an escarpment of a resistant stratum of the cover on the other (Fig. 135). This has been called by Davis[10] an "inner lowland" and by de Martonne[15] a "peripheral lowland".

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CHAPTER XII

Lateral Corrasion and Meandering Rivers

As rivers become mature and graded progressively farther upstream the cessation of rapid down-cutting (which has come to an end with the passage from youth to maturity) is quickly followed by changes in the cross-profiles on their valleys. Valleys become more widely opened, for the sides slope back from the stream banks more and more gently as the interfluves are lowered,* and at the same time flat valley floors develop and increase in width. During the stage of youth down-cutting has kept ahead of the agencies that tend to reduce the steepness of valley sides, so that the most these generally have succeeded in doing is to open the valley out to the typical V-shape. In the mature stage, when deepening no longer goes on rapidly, and may cease altogether for a time, erosion continues on the valley sides, which retreat with a tendency to develop more gentle slopes, but these are steepened from time to time at the base as they are undercut by lateral stream corrasion.

Lateral Corrasion

Lateral corrasion, the work of the river in the valley bottom, meanwhile develops a flat valley floor. Though the river is now graded and has ceased to cut rapidly downward, it still has abundant energy. Wherever its current is directed against the valley side the bank is attacked by undercutting and is caused to recede, and thus the floor is widened. Most rivers have already developed curvature in the stage of youth as an accompaniment of valley deepening (Fig. 27, p. 46). They wind between interlocking spurs in asymmetrical V-shaped valleys along the sides of which slip-off slopes alternate with undercut slopes. The windings, which are

* This is true in a general way whether the "down-wearing" or the "back-wearing" theory (Chapters XIV, XVI) furnishes the better explanation of the progress of erosion.

"meanders" of a sort, tend to develop with considerably wider radius of curvature than the flood-plain meanders described later in this chapter.[10]

Flood Plains

After such a river is graded enlargement of its curves still goes on, but, as lateral cutting is now no longer accompanied by vertical cutting, their further enlargement results in widening a flat valley floor. As the stream does not require the full width of the enlarged floor for its channel, it concentrates itself against the outer, or

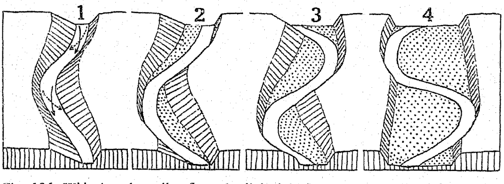


Fig. 136. Widening the valley floor. 1, slight initial curvature has developed during valley deepening into more symmetrical swinging in a valley with undercut and slip-off slopes; 2, 3, and 4, effects of lateral corrasion after valley deepening has ceased—trimming, sharpening, and blunting of spurs, and development of a flood plain.

(From *Geomorphology*, also by the author.)

concave, banks of its winding course, towards which it is impelled by centrifugal force; and it deposits the coarser material of its load of waste along the inner, or convex, banks, forming there flat areas of new land, which are covered by the river only at times of flood. These are the beginnings of a *flood plain* (Fig. 136). At first they are a series of short, crescent-shaped, but slightly sinuous strips that have been termed *flood-plain scrolls* (Davis) (Figs. 136, Stage 2; and 137).

The deposition of coarse alluvium (gravel or sand) along the convex banks of a stream that is enlarging its valley floor results in part from sluggishness of the current—and especially absence of turbulence in it[14]—along that side of the curved stream channel. There are, however, also cross-currents to be taken into account, an upper one of relatively clear water, not fully loaded with waste,

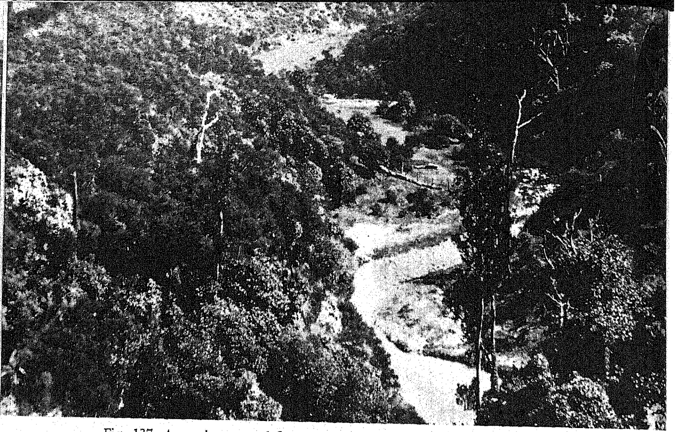


Fig. 137. An early stage of flood-plain development in the valley of the Kaiwarra River, Wellington, New Zealand.

that moves towards the outer bank, where it increases the corrasive power of the stream, and a return current along the bottom towards the inner bank (theory of "helicoidal flow").[17] This bottom water is laden with waste, much of which it drops in the sluggish water near the convex bank. The actual movement of water at any point is the resultant of the downstream and cross-stream currents. In the diagram (Fig. 136, 1) full arrows indicate the directions of currents in the upper layers of water, and the dotted arrows those of currents along the bottom.

Spur-trimming

Streams cut not only outward on curves, but also down-valley, being carried in that direction by an accelerating force due to the general slope. They thus cut into the interlocking valley-side spurs from the up-valley side, at first *trimming* them (Fig. 138), then *sharpening* them, and eventually *blunting* them,[6] or paring them off altogether (Fig. 136, 2, 3, 4). By the time the spurs are pared off a valley floor is occupied by a flood plain that is continuous except where interrupted by the river, and this flat valley floor is bounded at each side by a line of bluffs—the undercut slopes of the valley sides.

Cut-off and Narrowed Spurs

The process of spur-trimming and spur-sharpening is sometimes varied by intersection of two concave undercut slopes (amphitheatres) taking place, so that the neck of a valley-side spur is cut

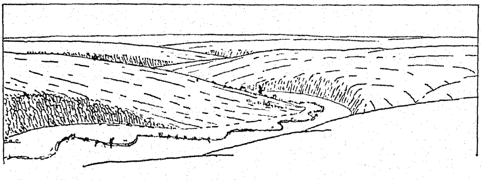


Fig. 138. Trimmed spurs in the valley of an English river, valley of the Windrush, looking west past Crawley. (After a sketch by Davis, redrawn.)

through. The river abandons the former course around the spur end and takes a more direct one through the new cut. Thus island-like *cut-off spurs* may remain for a time isolated and surrounded by the flood plain (Fig. 139). *Narrowed spurs* are those that have been reduced to peninsula-like forms where cut-offs are, or have been, imminent, the spur neck being in some cases thinned to a sharp and serrate form.

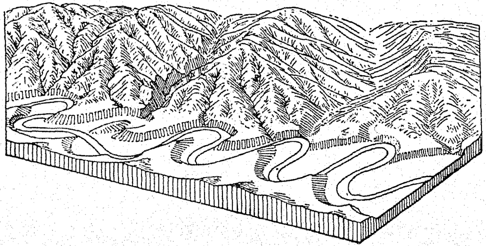


Fig. 139. Spur-trimming and flood-plain development in the valley of the Lamone (Italy), where a river is dissecting the floor of a valley of a former cycle. (After Davis.)

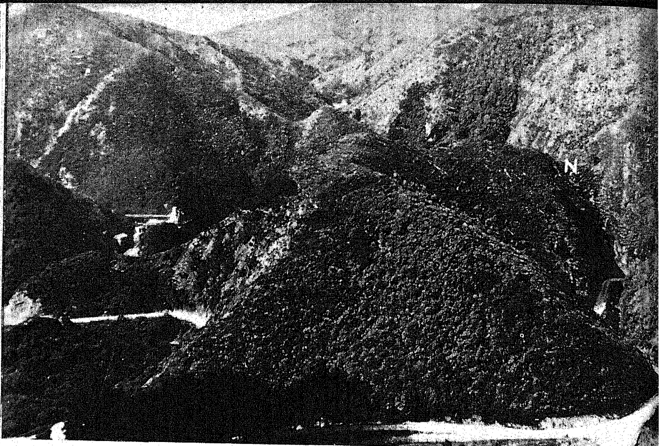
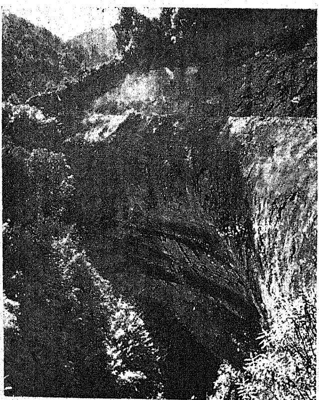


Fig. 140. Narrowed spur in the Ngahauranga valley, Wellington, New Zealand. A main highway has now been taken up this valley by way of a cutting through the narrow neck, *N*, of the spur.



F. G. Radcliffe, photo

Fig. 141. An undercut valley-side actually overhangs at the "Dress Circle", near Pipiriki, New Zealand.
(From *Geomorphology*, also by the author.)

Professor Herbert E. Gregory, photo

Fig. 142. The Rainbow Natural Bridge, Utah, a perforated spur.

Cutting-off and narrowing of valley-side spurs may occur even in river youth, where vertical corrasion is still going on as an accompaniment of lateral corrasion, especially in cases where relatively great lateral cutting accompanies valley deepening, as in the valleys of small streams in districts of deep dissection (Fig. 140).

Exceptionally, in tough, unjointed rocks, lateral corrasion undercuts valley-side slopes to such an extent that they overhang (Fig. 141), and so the neck of a narrowed spur may be cut through below and yet remain intact above, forming a *natural bridge* (Fig. 142). Natural bridges of this kind are less common than those developed by solution in limestone (Chapter XXIII).

Naturally, flat-floored valleys are opened out most rapidly in weak rocks. They are characteristic of dissected coastal plains (Figs. 66, 68), where erosion of uniformly unconsolidated materials is in progress, and of the weak belts of inclined and folded sedimentary formations which are occupied by the valleys of subsequent rivers. Another factor favouring rapid flood-plain development is small available relief, for in shallow valleys—that is, in those whose ultimate depths, limited by approach towards base-level, are small as compared with the ultimate breadth they may attain—a moderate

V. C. Browne, photo

Fig. 143. Winding valley of a tributary of the Awatere, Kaikoura Range, New Zealand.

amount only of waste has to be removed during the process of spur destruction. This condition is sometimes fulfilled where rivers in the current cycle are dissecting valley floors inherited from a former cycle that has been interrupted (Fig. 139).

Spur removal and flood-plain extension must also be considered as a stage in the development of mature landscapes in upland and highland regions of deep valley excavation. Fig. 143 shows a winding valley in the Kaikoura Mountains, New Zealand, with interlocking spurs. The idealised form of such a valley is shown in Fig. 144, *A*, and the stages *B*, *C*, and *D* represent development from this V-shaped (but already graded) valley, through an intermediate condition with flood-plain scrolls and sharpened spurs, to an open valley with continuous flood plain bordered by bluffs.

A continuous flood plain may also be termed a *valley plain*. During every flood the surface of such a plain has a layer of fine waste, or silt, deposited on it, owing to the checking of the current by friction when the flood water spreads over the plain as a thin sheet, the main flow of the stream taking place still (and with a velocity much greater than that at low-water times) along the

regular channel. The deposit of silt may become very thick, and at low water a large river may flow between high banks of this material at a depth of many feet below its flood plain, as, for example, in the case of large rivers of north-eastern Australia; but beneath such a silt deposit, thick or thin, there is normally a foundation of gravel, this being the ordinary channel-filling material earlier deposited as the river has changed its course in the process of lateral corrasion.

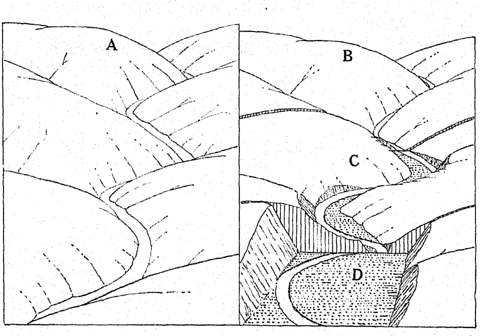
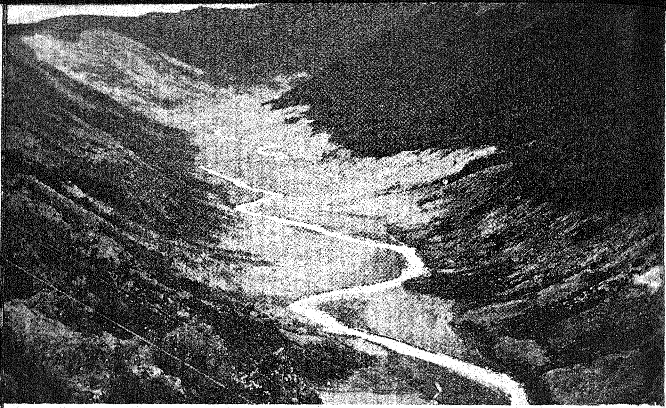


Fig. 144. *A* and *B*, winding valley with interlocking spurs; *C* and *D*, stages of the development of a flat-floored valley with flood plain bounded by bluffs.

Meanders

In the valley of a river that is cutting laterally, early formed twists and bends tend to develop into regular flowing curves even before the valley-side spurs have been trimmed off and the flood plain has become continuous. After that stage has been reached, and lateral corrasion is less impeded by the necessity of cutting through bedrock, free swinging of the river as it cuts away and redeposits its own alluvium allows of the development of symmetrical curves, or *meanders* (Fig. 145), proportioned in size to the stream so that the radius of meander curves comes to be about eighteen times the width of the river channel.[10]



A. R. Kingsford, photo

Fig. 145. Meanders on a continuous flood plain in the Upper Cobb Valley, Nelson, New Zealand. (There is evidence of the temporary occupation of this high-level valley by a small glacier, and it is uncertain how great a part glacial erosion has played in shaping it.)

The concave curves of a river on a flood plain may intersect, with the result that meanders are cut off in a manner similar to the cutting off of spurs, but with less expenditure of energy on the part of the river, which has now only the weak alluvial deposits on the flood plain to undercut—so that cutting off of meanders is of frequent occurrence. It is a means of automatic regulation of the size of meanders, preventing their overgrowth. When meanders grow in radius by continual expansion due to undercutting of concave banks, so as to reach the maximum size appropriate to the stream, continuation of the same process makes them S-shaped ("dovetail" meanders of Davis), adjacent meanders approach each other, and their banks intersect, a shortened course is adopted by the stream, and an overgrown meander is abandoned. (Even without actual intersection taking place, a stream in flood may scour a new channel across a narrow neck or burrow under it, or an ephemeral tributary may extend headward and effect a capture). The stream is relatively straight for a time, but soon develops new meanders *Cut-off meanders,* recognisable as "ox-bow lakes", which later owing to partial filling become swamps, are characteristic features of flood plains (Figs. 150, 151).

Misfit Rivers

It is sometimes found in a valley that has obviously been excavated and opened out by a river of considerable volume that the stream now present has meanders of insignificant size, which may be taken to indicate that serious shrinkage of stream volume has taken place. If the shrinkage has been of recent occurrence, traces of former larger meanders may still be present on the flood plain with the smaller curves superimposed upon them. This is a characteristic of the valleys of *underfit* rivers.

Deep valleys and also those with widely opened floors may appear to an inexperienced eye far too large to be reasonably explained as the products of stream erosion, or, at any rate, the observer may find it difficult to credit that they have been excavated by the small streams now flowing in them, so that he is mistakenly inclined to postulate the former existence of a large river where now there is but a rivulet. In order to guard against such wrong conclusions it is important, therefore, to examine the effects actually produced in valleys by changes in the volumes of streams such as may be reasonably expected to occur in certain circumstances—the shrinkage of streams, for example, that are beheaded.

A river too large or too small to have eroded the valley through which it flows is a *misfit* river (Davis). If too large (*overfit*) for its valley, a river will rapidly alter the form of the valley to suit itself, expanding its curves and so cutting into the valley sides, and generally at the same time deepening the valley (Fig. 82) to establish a new graded profile. The valley thus temporarily assumes features of youth such as may make it contrast strongly with the valleys of neighbouring rivers.

A river that has, on the other hand, shrunk until it is too small for its valley, is an *underfit* river,[6] and may be recognised as such, if it has a mature valley and well-developed flood plain, by the development of characteristic valley-floor features. Conspicuous among these is the shrinkage of meanders previously referred to. Many examples of such valleys have been observed and described, especially in cases of English, French, and German rivers that have been beheaded or have lost volume as a result of shifting of divides

associated with the retreat of escarpments. A classical example is the valley of the Bar, a beheaded tributary of the Meuse.[3] The Windrush, shown in Fig. 138, is also underfit,[4] and

in the neighbourhood of Withington, the form of the Coln valley [Fig. 146] suggests a progressive diminution of the size of the river that has followed it. There are, first, large-scale meanders, indicated by the general form of the curving valley; second, much smaller meanders indicated by concave nips or re-entrants at various points on the side-slopes of the large meanders; and, third, the minute contortions of the existing stream. (Davis.)

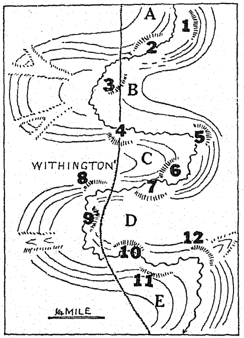


Fig. 146. Diagram of the valley of the Coln. "The spurs, lettered *A* to *E*, project into corresponding amphitheatre-like concavities, whose floor is above the present valley floor: thus the path of the original river at the time of its greatest volume is indicated. Successive concavities, numbered 1 to 12, are taken to represent indentations in the sides of the large meanders, caused by the river of medium volume. . . . The existing stream of small volume flows irregularly on the valley floors" (Davis). Thus successive stages of shrinkage leading to the present underfit condition have left their traces. (Map after Davis.)

Undercut slopes resulting from lateral stream corrasion at a time when streams flowed in full-bodied curves and were busily engaged in trimming spurs may still be traceable on the valley sides, but are now fading out of the landscape, as they are no longer kept fresh by continued undercutting. In the valley of the Smiecha, a tributary

of the Danube, for example, "nothing less than the centrifugal force of a large stream seems competent to originate a valley of so highly specialised a form"[4] (Fig. 147).

Tributary rivulets continue to bring their contributions of waste into the valleys of underfit rivers, but the main streams are incapable of transporting it all. Much detritus accumulates, therefore, as fans at the mouths of many small branch ravines, and these are

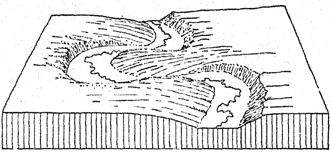


Fig. 147. Valley of the Schmiecha, a tributary of the Danube, at Kaiseringen, looking north. (After a diagram by Davis, redrawn.)

confluent with talus slopes fringing valley-side bluffs and under-cut amphitheatres, so that a former flood plain becomes more or less completely buried beneath these deposits, while portions that escape burial become swamps. Such valley-floor forms are conspicuous, for example, in the beheaded valley, now carrying a tiny underfit stream, shown in Fig. 148.

Lateral Planation

Lateral corrasion continues, with development of a valley plain of gradually increasing width (*lateral planation*), long after the first paring-off of projecting spurs and establishment of the first continuous flood plain. Early formed valley-side bluffs that have resulted from vigorous undercutting are reduced in steepness by the complex of valley-side erosion processes that are always at work smoothing out slopes to gentler declivities; but renewed undercutting occurs at one point and another from time to time, and fresh undercut embayments, or valley-side amphitheatres, are formed. At first, while the width of the valley floor is no greater than the *meander belt*, or belt bounded by lines tangent to the outer curves of meanders of full development in proportion to the size

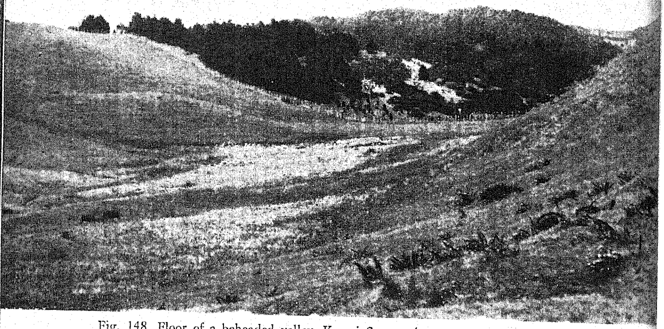


Fig. 148. Floor of a beheaded valley, Karori Stream (compare Fig. 86), Wellington, New Zealand, showing swampy floor and accumulation of slope debris at the sides resulting from the underfit nature of the rivulet now occupying it.

of the stream, every full-sized meander may be expected to pare a slice from the base of the valley-side slope as it migrates downstream, impelled in that direction by the same down-valley momentum that earlier caused the stream to trim spurs, but now no longer delayed by the necessity of cutting away solid rock (Figs. 149, 150).

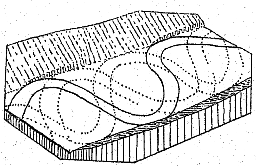


Fig. 149. Lateral planation accompanying downstream sweeping of meanders.

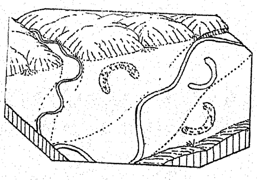


Fig. 150. Wide valley plain developed by lateral planation. The meander belt is bounded by dotted lines.

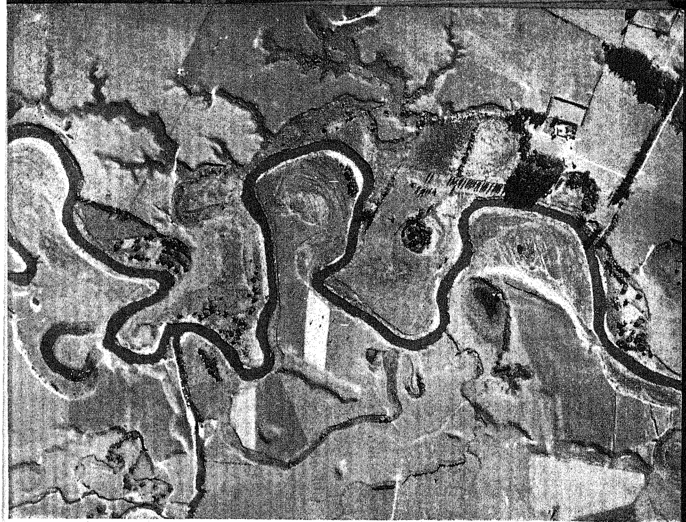


Photo from N.Z. Aerial Mapping Ltd.

Fig. 151. Meanders and cut-off meanders of the Waihou River, New Zealand.

The downstream migration, which has now become rapid, as the stream can cut laterally with great rapidity where it encounters only the small resistance offered by its own deposited alluvium, has been termed *sweeping*. Speeded up, as though by a trick of animated photography, the downstream sweeping of a succession of meanders might be likened to the writhing of a snake or the transmission of a series of waves along a slack rope or curtain. Thus old and new maps of the same river valley may show meanders in quite different positions and of quite different shapes; and all vertical photographs of valley plains indicate the presence of many cut-offs and ox-bow lakes (Fig. 151).

Wide Valley Plains

As the valley plain grows wider meanders impinge less frequently against the bedrock of the valley sides, but from time to time one pares a slice from it, as the meander belt, itself of writhing and changing form, swings to that side of the valley floor.

The development of open, wide-floored valleys naturally goes on most rapidly in weak rocks; and so in a region of alternately weak and resistant rock outcrops the valleys along weak-rock belts (together with such portions of transverse valleys as cross these belts) are widely opened out as subsequent lowlands (Fig. 71), which are in part wide valley plains, while transverse streams where they cross resistant formations are still in narrow water gaps.

Interfluves may be cut through by lateral corrasion, and diversion (by *abstraction*) of smaller streams to become tributaries of larger neighbouring streams may occur. Even adjustment to structure may be to some extent destroyed in this way.

The process of lateral corrasion, or "planation", at a stable gradient, or at constant level, cuts a bedrock floor (only thinly veneered with a flood-plain deposit of alluvium) which is nearly plane (if the slight concavity of the longitudinal profile of the river be disregarded), but which, in theory, must be slightly convex in transverse profile, as it is part of the surface of a very flat cone with its apex at the source of the river—and this is seen to be the true form when rising flood waters first invade strips close to the valley sides. Small streams of steep gradient have indeed occasionally succeeded in cutting laterally far enough to develop small "plains" that are quite strongly convex. Davis[5] has called these *rock fans*. Some steep and strongly convex examples of this form have been found by Johnson[11] and others in the desert ranges of the American South-west.

It is but a step farther to take up the debatable question of the probability of the development of extensive "plains of lateral planation", but the process of lateral corrasion by aggrading streams must first be touched upon. In the foregoing discussion of lateral corrasion the behaviour has been considered of streams with well-defined rather deep channels, which develop and continue to flow in meandering courses. Such are the channels of streams not over-supplied with waste, but yet fully loaded, for otherwise they would continue the process of valley deepening. Any coarse waste that is available for deposit is built into the basal part of the flood-plain veneer on convex and down-valley-facing banks of swinging and sweeping meanders, and this is afterwards buried to a varying depth beneath the silt spread during floods. Coarse waste is not available for deposit in such quantities as to fill up the channels of the streams

and so cause them to flood frequently, to spill over sporadically into new channels across the flood plains, and to spread layers of coarse waste over the valley floors.

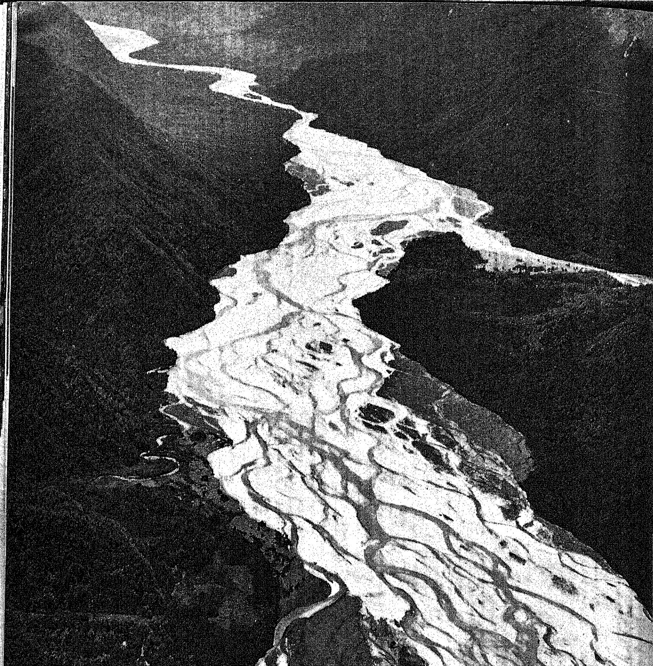
Braided River Courses

In streams with these latter characteristics, typically flowing in anastomosing, or *braided,* channels (Fig. 152), as contrasted with the well-defined meandering courses previously described, the very fact that they flow in such unstable channels is sometimes taken as proof that coarse waste is being deposited over the actual stream beds, raising them so as to cause the streams to distribute themselves into new channels which are in turn built up and abandoned, so that the level of the whole flood plain is raised, and the river is *aggrading*. In the present state of knowledge, however, it is not asserted that all streams in braided courses are positively aggrading. It is known, on the other hand, that some aggrading rivers of low gradient flow in meandering courses, building up their flood plains with layers of silt spread during floods.[16]

Aggrading streams in ever-shifting, ill-defined, braided channels are capable of lateral corrasion. Their lateral-cutting ability, indeed, seems greater than that of meandering streams,[7] probably because the currents in some of the many channels more frequently strike against the valley sides. Beginning the process of lateral corrasion combined with aggradation in a V-shaped valley (Fig. 153, *A*), a stream may be expected to cut a more broadly open V floor (*C*), with smoothly cut, inclined side slopes that may be either nearly plane or of varying inclination, but these will be buried, progressively as they are cut, by the alluvial deposits of the aggraded flood plain (*B*). Very probably well-directed search will reveal examples of such V floors exposed by later stripping away of the alluvial cover, though they are likely to be modified by development of terraces during such stripping. Obviously, the slower the rate of aggradation accompanying lateral corrasion, the more nearly level will be the floor cut on the bedrock of the valley, and the thinner the alluvial veneer upon it.

Plains of Lateral Planation

According to some authors a very important part has been played by streams in developing extensive plains by lateral corrasion. Such



V. C. Browne, photo

Fig. 152. Braided course of the Arawata River, New Zealand. The river is still spreading gravel over a delta with which it has filled in a fiord.

plains of lateral planation have been termed also "panplains" by Crickmay.[2] The theory is applied in particular to the planation of zones peripheral to mountains, where "the flood plains of adjacent streams coalesce to form continuous plains".[8] Gilbert[8] figures an "ideal sketch" of a landscape with such a continuous plain bordering a mountain front. He describes the streams responsible for the planation as flowing in shifting channels. Variation in the supply of

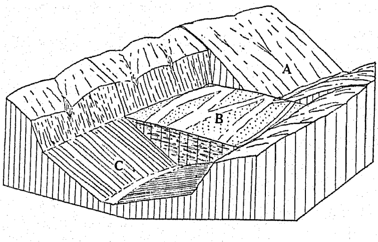


Fig. 153. Lateral corrasion accompanying aggradation.

waste to a stream sometimes fills its channel to such an extent that it spills over into a new one. "The abandoned courses remain plainly marked. . . . Where a series of streams emerge from adjacent mountain gorges upon a common plain their shiftings bring about frequent unions and separations, and produce a variety of combinations."

The *pediments* of arid and semi-arid regions—sloping plains bordering dissected mountains in a late-mature stage of landscape dissection — are thus accounted for by Johnson,[11, 12] while other observers agree that lateral corrasion at least takes part in their formation, though perhaps not the dominant process. It is well understood that running water, ephemeral as streams may be in a desert, does an important part of the work of erosion in most if not in all deserts. So reference to the theory of lateral planation in arid and semi-arid regions is not out of place here, though a more complete discussion of pediments cannot be attempted without consideration of the whole desert landscape. Johnson has made

the further suggestion that many high-level now-dissected surfaces generally thought to be parts of uplifted peneplains would be more correctly explained as plains of lateral planation,[12] and Howard[9] has applied this pedimentation hypothesis specifically to high plateau surfaces in the Rocky Mountains. The reference made by Johnson[11] to high-level benches in the South Island of New Zealand as possibly the inner margins of once vast plains of lateral corrasion necessitates consideration of the process of wide planation in its possible application to humid as well as arid and semi-arid regions. A suggestion has been made that coastal benches also along the east coast of the South Island (which are marine terraces at least in part) may have been shaped prior to a temporary submergence by the pedimentation process.[13]

The essence of the theory of efficient lateral planation producing plains, as developed by Johnson, is that, where streams are actively eroding in their headwaters, deepening their valleys there and gathering loads of waste, and in their lower courses are depositing waste and aggrading their floors, as streams must do, for example, in arid deserts, there is a middle portion of their courses in which they are neither downcutting nor upbuilding to a cumulative extent, and in which, therefore, lateral corrasion will take place at a fixed level, so that in this middle part of their courses the streams are competent for, or capable of, planation. Where adjacent streams from mountains are similar in this respect there may be a "zone of lateral planation", as Johnson terms it, in their middle courses, in which the streams cut through and later obliterate the divides between them so as to develop a continuous plain. Across this plain the rivers will continue to flow, each on a radius of its own rock fan. Considerable irregularity of surface, one may note, is to be expected in the early stages of development of a plain made up of coalescing rock fans, for adjacent large and small streams will be at different levels and have different gradients. Abstraction of the smaller streams when divides are breached, followed by their regrading to lower local base-levels, will interrupt the continuity of the process of lateral planation, and much of such integration of drainage will be permanent, at least if it takes place in humid regions.

In an arid climate, it has been pointed out, the streams of a theoretical zone of lateral planation, though not actually aggrading,

are intermittent in their flow, and when they flow, or flood, bring down much coarse alluvium. They do not, therefore, flow in swinging, sweeping meanders, but, on the contrary,

> accumulation of debris tends to block the channel, the stream spreads, cross currents are set up, and braiding develops rather than meandering. The heavy load favours lateral planation . . . by favouring . . . lateral displacement through accumulation of debris along and within the channel. Since there are a multitude of interlacing channels, no one of them need shift very far in order that lateral planation should take place. (JOHNSON)[12]

The veneer of alluvium on the cut surface is thin, discontinuous, and composed of coarse, largely unsorted gravel, and is thus very different in character from that covering the flood plains of meandering rivers.

There is in New Zealand an extensive lowland, the Maniototo Plain, much of which has been formed by coalescence of valley plains of lateral planation developed by parallel streams from the northern highland of Otago. This lowland is in part a "local peneplain" on soft rocks.[1] Though the streams that cut the plain have since terraced it to some extent (Fig. 154), the southward

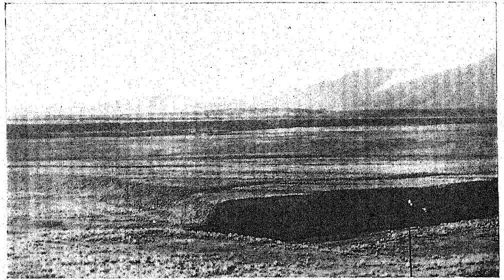


Fig. 154. The Maniototo Plain, largely a plain of lateral planation slightly modified by renewed erosion. The rear boundary of the plain is defined by the fault boundary of the northern highland of Otago, which is composed of relatively very resistant rocks.

(From *Geomorphology*, also by the author.)

slope of the whole feature is conspicuous to the eye (Fig. 155), and suggests alluvial fans, but the plain is a surface of planation, though cut on very weak materials only and not extended back into the hard-rock mountains at the rear, which are separated by faults from the weak sediments underlying the plain.

Rock fans and plains made up of confluent rock fans, like all other cut surfaces, must be subject to renewed dissection when local base-levels are lowered. Such lowering may be brought about by general or local uplift, but its occurrence does not necessarily imply uplift of the land or lowering of the general base-level. Under arid and semi-arid conditions the graded parts of the streams con-

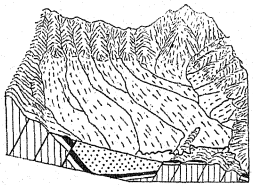


Fig. 155. The Maniototo Plain. (After Benson, redrawn.) (From *Geomorphology,* also by the author.)

cerned in the planation of such a surface have steep gradients on account of the great loads of waste they are bringing down from their headwaters (in the case where these are dissecting mountains that are still of strong relief), and under the postulated climatic conditions there is not a very large volume of water to carry this load. These steep gradients are subject to reduction in the course of the cycle as less waste becomes available for transport from the mountains of dwindling relief in the headwater zone. Downcutting to weaker gradients lowers local base-levels along the streams and must result in planation at successively lower levels. With uniformity of conditions such lowering of stream gradients will be very gradual, and the entire surface of a pediment that is for the most part a plain of lateral planation may be lowered simultaneously. Some streams that remain fully loaded (owing to some local circumstance) may maintain their gradients unchanged, however, while

others that are affected by a falling off in the supply of waste cut downward; and as a result occasional captures (similar to that of the Greybull River, referred to in Chapter VIII) may eventuate, and this will lead to some terracing of the pediment,[15] but such effects are generally of importance only in the special case where the mountain front at the rear of the pediment is retreating rather rapidly as a structural escarpment.

Such circumstances as small climatic oscillations sufficient to affect the vegetation and through it the rate of erosion on the mountains may cause surges of erosion resulting in terracing due to alternation of phases of vertical and lateral corrasion. Terrace development and survival of mesas and bench remnants of higher plains due to such causes may be indistinguishable from the effects of upwarping, of lowering of local base-levels owing to changes in river courses, and of major climatic oscillations.

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CHAPTER XIII

River Terraces

GILBERT HAS WARNED US AGAINST "THE ERROR OF SUPPOSING THAT RIVER terraces in general are the records of sedimentation, when in fact they record the stages of a progressive corrasion".[17] "River terraces", he tells us, "as a rule are carved out, and not built up. They are always the vestiges of flood plains, and flood plains are usually produced by lateral corrasion." In addition to the "river" terraces which Gilbert describes there are also, of course, structural terraces (Chapter X), step-faulted strips and splinters* (Chapter XXII), terrace-like stranded lateral moraines and kames related to glaciers of a bygone age, and remnants of shoreline features and deltas of former lakes, which may now border river valleys, as well as, possibly, bench-like relics of former pediments, or plains of lateral planation, bordering mountains (Chapter XII), and of emergent wave-cut platforms, forming marine terraces, parallel to the sea margin.

TERRACES DUE TO LATERAL CORRASION

River terraces may, however, be defined (following Gilbert)[17] as terraces that border river valleys and mark former levels of flat valley floors such as have resulted from either corrasion or valley filling. The latter must be rare, however. The materials out of which terraces are cut have, indeed, frequently been formed by valley filling, and are then in some cases river-laid; but terrace formation is essentially, as Gilbert insisted, an accompaniment of valley formation by corrasion, alternately vertical and lateral; and the material filling a former valley is best regarded merely as a part—a softer part—of the rock out of which a new valley has been

* Strips of valley floor may be raised up by earth movement along faults in the valleys of which they form part so that they become terraces along one side—the upheaved side—of the valley only. In New Zealand there are conspicuous terraces of this anomalous and hitherto unclassified kind along the south side of the Hanmer basin plain, Canterbury, and along the north-west side of the Hutt Valley, Wellington. (Fig. 340.) These are river terraces of a "unilateral" variety.[13]

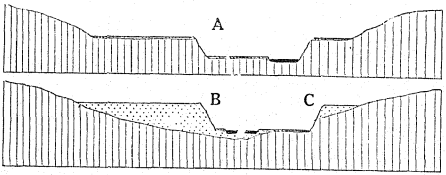
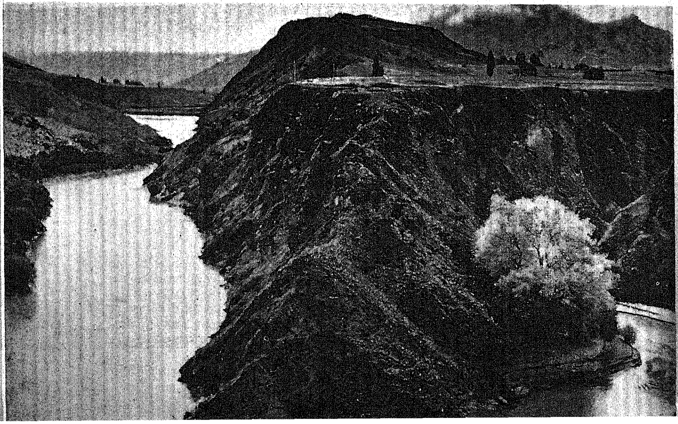


Fig. 156. Terraces cut on bedrock, *A*; and on valley-filling gravel, *B, C.*

cut. The "treads" or tops of terraces, except where burial beneath alluvial fans and screes has taken place, are almost always parts of flood plains cut by lateral corrasion, though sometimes in bedrock and sometimes in valley-filling alluvial gravels or lake silts.

River terraces cut across bedrock by lateral stream corrasion must be distinguished from structural terraces, such as have been described in Chapter X and are sometimes erroneously classed with

Fig. 157. Cyclic terrace cut on hard rock at the junction of the Arrow and Kawarau Rivers, New Zealand. *V. C. Browne, photo*



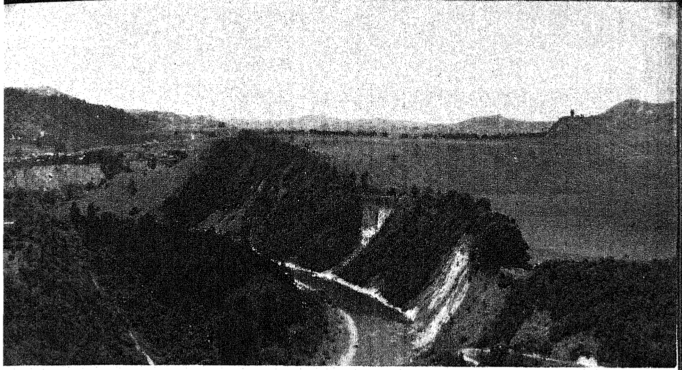


Fig. 158. Cyclic valley-plain terraces and incised (ingrown) meanders in the valley of the Rangitikei River, western Wellington, New Zealand.

river terraces. Many river-made "rock terraces" are "valley-plain terraces" equally with those that are underlain by thick gravel beds (Fig. 156, *B*, *C*; 160), though in this case the gravel overlying bedrock is only a thin veneer (Figs. 156, *A*; 157).

In New Zealand—a land of terraced landscapes—terraces both of bedrock with thin alluvial veneer and of thick alluvium are

Fig. 159. Terraces bordering the Esk River, a tributary of the Waimakariri, Canterbury, New Zealand.

V. C. Browne, photo

V. C. Browne, photo

Fig. 160. A valley-plain terrace cut out of alluvial valley-filling gravel, at Cromwell, Clutha Valley, New Zealand.

common. The abundant terraces in the valleys of the rivers of western Wellington are cut on soft bedrock (Fig. 158). Equally abundant are the terraces of Canterbury, cut in the thick gravels of the Canterbury Plain (Fig. 125), and gravel terraces are present in many inland valleys that have passed through phases of deep aggradation—for example, a great series of terraces in the Esk valley (Fig. 159) and some other deeply gravel-filled valleys in North Canterbury, the terraces of the Shotover valley (Fig. 170), and those of other parts of the Clutha valley system (Figs. 160, 248).

Valley-plain Terraces

While all ordinary river terraces are in a sense valley-plain terraces, this term has been applied[9, 10] particularly to those that are remnants of the broader valley floors developed by rather wide planation (especially in soft materials) in what are generally regarded as partial cycles of erosion, or rather long halts in discontinuous uplift of the land, as contrasted with the narrower or discontinuous flood plains developed in relatively short pauses in almost continuous vertical corrasion.

V. C. Browne, photo

Fig. 161. Valley-plain and minor terraces, Broken River, Canterbury, New Zealand.

Cyclic or *valley-plain terraces,* as thus defined, are surviving parts of formerly continuous valley floors cut by rivers to widths often very much greater than those of the immediate present-day valleys that have been incised in them in more recent episodes of vertical corrasion, followed generally by renewed lateral corrasion. If such has been the sequence of events, valley-plain terraces of matched height may be present facing each other on opposite sides of a valley (Fig. 161); but if, on the other hand, the former valley has been little, if any, wider than the inner or immediate valley of the river is now, the cutting of the latter will have very largely destroyed the higher valley plain, though remnants of it may be preserved here and there on both sides of the valley, and those on one side may be matched with those on the other and isolated remnants correlated as parts of the same once continuous flood plain.

Valley-plain terraces of more than one episode, minor cycle, or epicycle of lateral planation may border a valley, and such terraces have a fair chance of preservation in places if the later planations were successively less extensive. Matching terraces on opposite sides of a valley are then found (Figs. 161; 173, *A*). Terraces of this

kind are described by French authors as *terrasses emboîtées* (translated by Barbour[1] as "inset terraces").

Slip-off Slope Terraces

Even brief halts in at least the last episode of vertical corrasion may be recorded by terraces; but these generally escape preservation except on the slip-off slopes of spurs facing the undercut amphi-

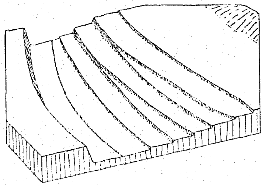


Fig. 162. Pattern of terraces on a slip-off slope, Awatere River, New Zealand. (From *Geomorphology,* also by the author.)

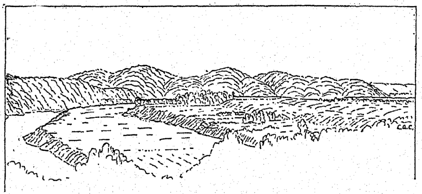


Fig. 163. Slip-off slope terraces, Jackson River, Virginia. (Described by Wright.)[32]

theatres in expanded curves of the inner valley. Such spur ends are commonly broken by a number of *slip-off slope terraces,* as they may be called[9] (Figs. 162, 163). Even in such a situation, however, some terraces are nearly always destroyed as lower ones are cut, correlation of the patterns of terraces from spur to spur becomes uncertain, and the inferred pauses, or epicycles, which punctuate the upheaval, or episode of vertical corrasion, during which the terraces

were cut can rarely be established with certainty. The convex outlines of the fronts of terraces on a slip-off slope are related very simply to the convexities of the valley-side spurs on which they are cut. Terraced slip-off slopes may perhaps be regarded as the rule, not the exception. Where these slopes are smooth, indeed, and apparently unterraced this condition may be regarded as the result of integration of a large number of small terraces. Thus a smooth slip-off slope is termed by Chaput[8] a "polygenetic terrace" (*terrasse polygénique*).

Slip-off slope terraces can survive no longer than the valley-side spurs on which they are cut, and are, therefore, ephemeral. Valley-plain terraces may be longer lived, though in constant danger of destruction as valleys are opened out to greater width. All river terraces are, indeed, definitely features of landscape youth.

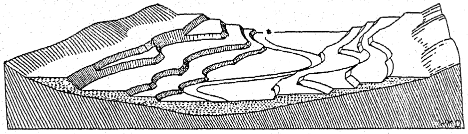


Fig. 164. Terraces of easily eroded valley-filling gravels protected by re-exposed outcrops of buried spurs. The protecting outcrops of bedrock are shown as black spots. (After Davis.)

Rock-defended Terraces

Rock-defended terraces, even though they may be narrow, stand a chance of much longer survival than those whose preservation is purely fortuitous in that they are at the mercy of the capricious swinging of an uncontrolled meander belt. Terraces in this category are generally defined as those having hard bedrock (which underlies alluvial gravels or other easily eroded valley filling) exposed at the base of the terrace front in such manner as to have stopped, or at least restrained, lateral stream corrasion that has at some time threatened to undercut and destroy the terraces (Figs. 164, 165), together, of course, with all other valley-side forms;[14] but similar exposure of outcrops of more resistant members of a bedrock sequence may be equally effective in checking lateral planation and so preserving as terraces parts of flood plains cut on easily eroded softer members.

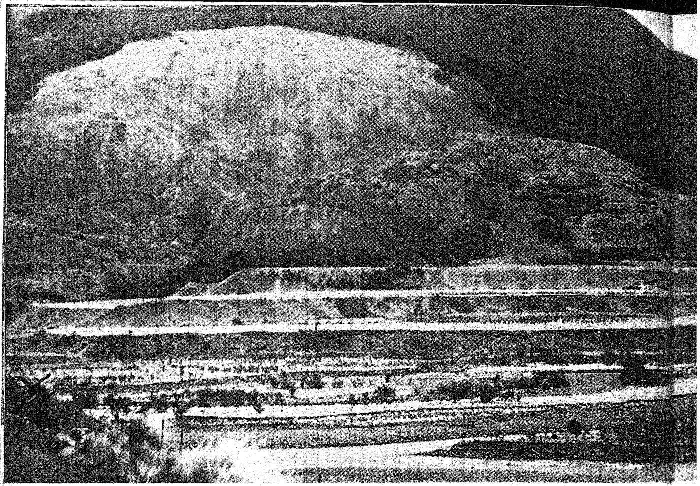
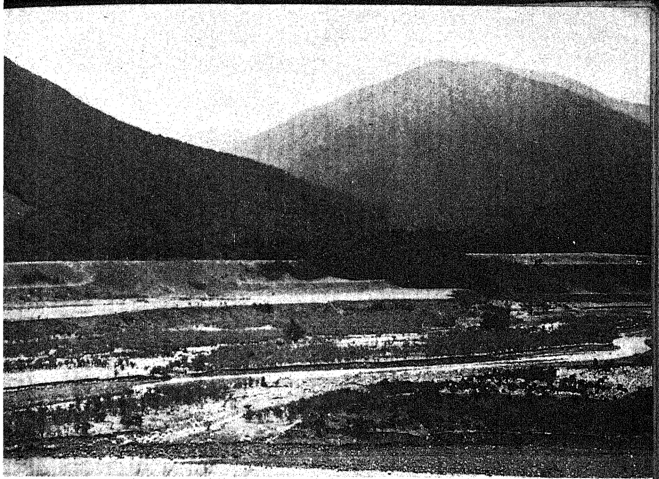


Fig. 165. Flight of meander-scar terraces at the confluence of the Doubtful an Boyl
part of lacustrine deposits, under which is the buried continuation of the glacial mai

Outcrops that are particularly effective in defending terraces occur most commonly at valley constrictions, or gorges. At such a point, where perhaps a river is superposed on a buried ridge (Fig. 204), or crosses a spur that has been buried in alluvium deposited by the river itself (Figs. 166, 170), or where it encounters any resistant rock outcrop, sideward-swinging meanders both upstream and downstream from the gorge take concave bites out of the terrace fronts, and such concave fronts (in plan) are characteristic of rock-defended terraces, two concave fronts meeting in a cusp on each defending rock outcrop (Fig. 164). They are for this reason commonly called *meander-scar terraces.*

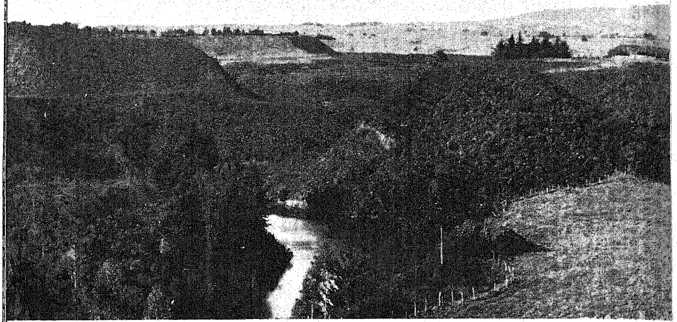
Convergence of concave-fronted (meander-scar) terraces on a defending gorge in the Broken River basin, New Zealand, is shown in Fig. 167; these are rock terraces (i.e. consist of planed bedrock). Fig. 168 shows terraces converging on the debouchure of the Rangitata River (New Zealand) from a mountain gorge on to the trenched alluvial plains of Canterbury (compare Fig. 169). A



e Rivers, Lewis Pass highway, New Zealand, cut in valley-fill consisting in
nillated spur seen above.

peculiar example of defended terraces in alluvium is afforded by a "flight" in the upper valley of the Shotover River, New Zealand, (Fig. 170). The river has been superposed from a course on its own alluvium on to hard bedrock (buried spurs) by the side of the valley which it had previously filled with gravel, and it has cut the terraces on the gravel filling while swinging between nodes fixed by gorges thus cut through the buried spurs.

Any constriction in a valley may have an effect similar to that of a rock gorge in defending terraces. Such constrictions may be formed in mountain valleys by fans of alluvium built by tributary streams, which may maintain their position, if the supply of gravel is sufficiently copious, while the level of the main valley floor is being lowered. By forcing the main stream towards the opposite side of the valley they prevent its wide swinging, and form nodes in a manner similar to gorges; or, at least, they prevent swinging towards their own side, and thus defend terraces. Examples have been noted in the upper Rakaia valley, New Zealand.[30]

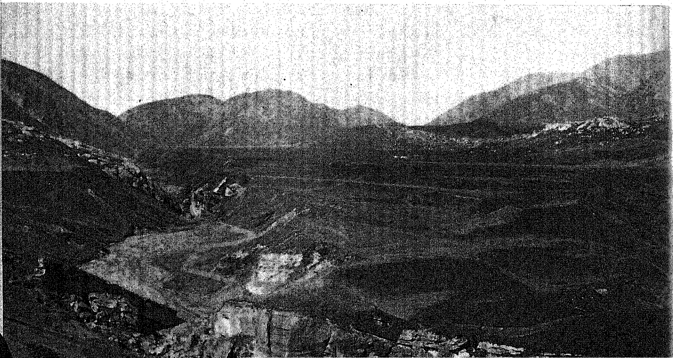


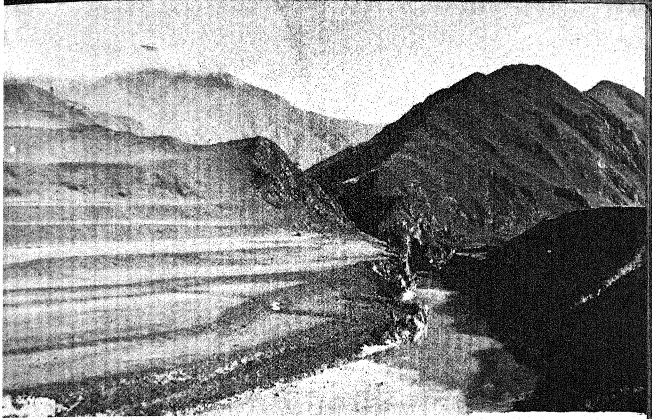
N. H. Taylor, photo

Fig. 166. Terraces of the Waikato River, New Zealand, cut in very weak pumiceous alluvium and defended at a point where the river is confined in a gorge as a result of being superposed on a buried valley-side spur (at Karapiro).

Fig. 167. A valley constriction (in the distance) protects terraces cut in soft bedrock, Broken River Basin, Canterbury, New Zealand. The constriction is the outlet gorge through hard rocks from an intermont tectonic basin.

Professor R. Speight, photo





Professor R. Speight, photo

Fig. 168. Terraces bordering the Rangitata River, New Zealand, where it emerges from its mountain gorge (at the right).

NON-CYCLIC TERRACES

The conditions of structure that provide terrace-defending rock outcrops may also determine a very slow rate of vertical corrasion. The superposition of the stream on bars of hard rock where it encounters buried spurs in a filled valley (Figs. 170, 171), or its transverse course through hard-rock strata or other barriers, may so

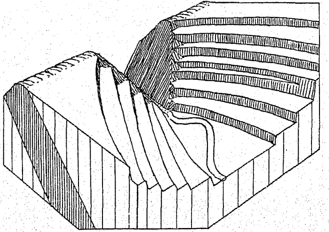


Fig. 169. Development of terraces progressively with the cutting of a gorge through a hard-rock bar. (Compare Fig. 168.)

V. C. Browne, photo

Fig. 170. Terraces in the upper valley of the Shotover River, New Zealand. At the right, excavations made by sluicing for gold reveal the former valley, gravel-filled.

slow down the rate of vertical corrasion that in adjacent areas of softer materials it maintains during the slow process of valley deepening a continuously graded, fully mature, and broadly opened valley. A similar result may conceivably be brought about by

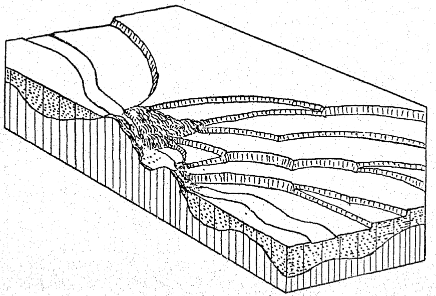


Fig. 171. Terrace development in soft alluvium where discovery by the stream of a buried spur of resistant rock has restrained vertical corrasion. (After a diagram by W. M. Davis, redrawn.)

extremely slow uplift of the land. In such cases a river, in its graded reaches, must continue during downcutting to maintain a meandering course on a flood plain; the meanders will migrate downstream, and the meander belt will swing from side to side of the valley floor. Since, however, the stream is continuously cutting downward, each time the meander belt approaches the valley side its floor is at a lower level than that of the previous time. If it quite reaches the valley side, it will completely cut away the former flood plain, but if not it will leave a remnant of it as a terrace[14] (Fig. 172). Terraces such as these are not commonly found in valleys of rivers that are excavating in homogeneous material, even though it be soft, for in this case there is no limit to the lateral swinging of the meander belt at the lower levels, and so the higher floors are

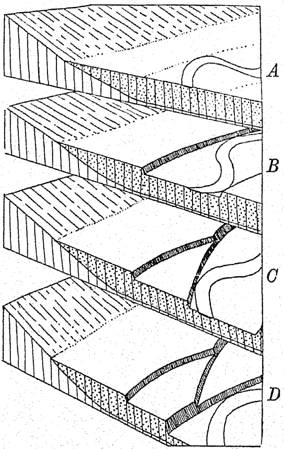


Fig. 172. Terrace development by a river that is deepening its valley very slowly in soft material. Stage *B*, the highest terrace, is a remnant of the valley plain, *A*; *C* and *D*, later stages, in which lower terraces are cut at successive flood-plain levels. Between each stage and the next the meander belt swings away towards the other side of the valley and returns at a lower level.

destroyed as new ones are developed. Remnants of the higher-level flood plains do commonly survive, however, where defended by hard-rock outcrops in the valley sides (Figs. 164, 165) or in gorges (Figs. 166-171), and some members at least of most flights of concave-fronted terraces have originated thus as *terraces of continuous valley excavation during restrained downcutting.* They are often classed simply as meander-scar terraces, though not all such concave-fronted terraces are of similar non-cyclic origin.

In some cases it is possible to distinguish terraces of this kind from those marking halts or discontinuities of vertical corrasion, for, unlike those of the latter kind, they will fail to match, where

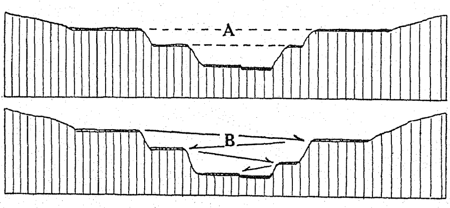


Fig. 173. *A,* valley-plain terraces matching in level on opposite sides of a valley ("inset" terraces). *B,* alternate terraces developed during continuous valley excavation; arrows indicate swinging of the meander belt.

present on both sides of a valley. Instead of matching (Fig. 173 *A*) successively lower terraces will alternate (Fig. 173 *B*) on opposite sides owing to the fact that an appreciable interval of time has elapsed during each swing of the meander belt across the valley, allowing it to be cut to a lower level. Where there is an appearance in opposed flights of terraces of matching of some terraces and alternation of others, it is probable that the flights are of composite origin, some being cut during halts and others during slow down-cutting.

Terraces Due to Lowering of Base-Level

Probably the commonest cause of a renewal of vertical corrasion in rivers, such as results in the development of terraces, is upheaval, or lowering of the general base-level relatively to the land—that is,

either regional uplift or eustatic emergence owing to lowering of sea-level. Equally effective where it occurs, however, is local uplift, which will be accompanied by warping or dislocation and tilting of the surface. A river may be shortened (betrunked) by rapid cliff recession at its mouth due to marine erosion, and this accident also will result in revival of vertical corrasion in the river. The process is not necessarily continuous at a uniform rate, and if intermittent it may result in terrace formation in the valley of the river. Small rivers with short courses to the sea are most readily affected by this cause of terracing.

Terraces that Indicate Change of Climate

A change of climate from less to greater humidity has also an important effect on the regimen* of streams. Even a small change not only provides more water, but also may appreciably reduce the load of waste to be transported by encouraging increased growth of protective vegetation in the catchment areas of the streams; and every change in the ratio of waste to water in a river demands a considerable adjustment of the gradient of its graded profile, resulting, especially far inland, in great changes in local base-levels. Terrace-making may be a result of such adjustment brought about in an episode of vertical corrasion, which will isolate portions of an earlier flood plain as terraces. Aggradation may have thickened the gravels on this flood plain (later to become the terrace treads) in a preceding dry-climate phase.

This thesis was developed by Huntington,[20] and may be termed Huntington's principle.[12] It implies that all episodes of increased precipitation (and the question arises whether it is necessary here to include glacial epochs, p. 203) will be characterised by degradation, at any rate in non-glaciated valleys, whereas dessication will cause aggradation by increasing the ratio of waste load to water in the rivers. The contention implies a nice state of balance between erosion and vegetational protection of slopes in the catchment areas from which the bulk of river-carried waste is derived. It is based on an argument certainly applicable where, as Barbour[1] has expressed it in a discussion of the Kalgan region (China), "conditions are so nicely balanced that erosion can start and be arrested again" as a protective

* "Rule of river action under which the balanced condition is developed and maintained" (W. M. Davis, *Geographical Essays*, p. 391).

cover of vegetation is depleted and re-established. The principle seems, however, not to be of universal application.

In some circumstances indeed the episodes of cutting that result in the abandonment of parts of flood plains as terraces (and also, of course, aggradational phases) may be due to changes that are the reverse of those envisaged by Huntington, though the reason for such a condition is not always apparent. Russell[27] regarded this, however, as the general case and assumed that streams would always cut downward more vigorously in the episodes of drier climate. Controlling conditions are probably not the same everywhere, but Russell's assumption is supported by the observations and conclusions of Bryan concerning the causes of alternate alluviation and erosion in the valleys of the semi-arid south-western region of North America. In New Mexico Bryan has correlated with prolonged droughts the arroyo-cutting and terrace-abandoning episodes that have occurred in recent ages between stages of alluviation.[4] In that dry region it is observed that "a slight change from the dry towards the less dry in climate is adequate to convert ephemeral streams from a condition of erosion to alluviation"; and "lack of rainfall was the cause of cutting of arroyos".[5]

Even in regions with abundant rainfall it is possible to imagine conditions under which increased precipitation will lead to such an increase in the ratio of load to water in a river that it must aggrade down the valley, while the reverse change will lead to deepening of the valley. At the headwaters the vegetation may be too little affected by an oscillation of climate in the direction of aridity to modify its function of protecting the soil from erosion, whereas when precipitation increases beyond a certain point even in a forested region flood effects and accelerated mass movement on slopes will swell the output of waste out of proportion to the accompanying increase in the volume of off-flowing water, thus causing aggradation rather than degradation down the valleys.

One may say there is a level of precipitation, probably a moderately low one, at which, apart from human interference, there is a close vegetative cover and geological erosion is at a minimum; any appreciable departure from this level of precipitation in either direction will cause increased geological erosion in the upper courses of streams, and hence increased deposition in their lower courses (Richardson).[26]

It has often been assumed that important episodes of alluviation are to be correlated with glacial epochs in non-glaciated and periglacial regions, and that terrace-cutting takes place in warmer, though not necessarily drier, climatic intervals.[25] This latter statement, however, applies to inland regions only, for near the sea the rise of the ocean level due to release of water from melted glaciers (glacio-eustatic) will lead to aggradation in interglacial intervals,[15a] whereas rejuvenation of valleys will take place in glacial stages when sea-level is low. Though it has sometimes been taken for granted that glacial epochs have been also pluvial epochs outside glaciated areas,[16] effects such as the accumulation of water as large overflowing lakes which existed for a time in semi-arid interior basins may be attributed not only to increased precipitation but also to greatly reduced evaporation in a glacial epoch;[20a] and the latter may be the sole cause of such accumulation.[24] If the climates of periglacial regions were characterised by high precipitation (as compared with that of interglacial epochs) the facts, or what are generally assumed to be facts, that alluviation has been contemporaneous with glaciation and that the cutting and abandonment of terraces have taken place in interglacial stages directly contradict Huntington's pronouncement; but on the alternative hypothesis that periglacial regions had a relatively dry climate the explanation of terracing presents less difficulty.

Zeuner,[33, 34] who attributes the theory to Soergel,[29] points out the probability that the climate of the European periglacial zone has oscillated between "humid-temperate" and "dry-cold", the latter being the condition in glacial epochs. If this interpretation is correct, terracing in such regions can be explained according to Huntington's principle. To quote from Zeuner:

Most of the rivers of this zone had their sources in the moderately high mountains between the Alps and Scandinavia, many of which had ice-caps of an inconsiderable size or none at all. In the warmer and damper interglacial phases between two glacial phases the climate was much like that of the present time. The rivers were cutting, and the country, not yet affected by man, was covered with dense vegetation, making superficial removal of weathered materials by denudation nearly impossible. Chemical weathering prevailed, and the rivers received mainly fine-grained detritus. As precipitation exceeded evaporation, the streams and rivers were constantly flowing, carrying considerable volumes of water, and strongly eroding.

When the climate became colder, however, the influence of weathering by frost action increased in the higher parts of the mountains. The forests retreated from the higher parts of the ridges, and the more effective mechanical processes of weathering now prepared large quantities of coarse and fine rock waste, which slowly moved into the valleys. The more severe the conditions became the more solifluction increased, carrying large amounts of waste into the rivers. . . .

Meanwhile the ice-sheet of Scandinavia extended, and a barometrical anticyclone developed over it. This caused the climatic conditions to become colder and drier at the same time; the forest even in the lowlands disappeared more or less completely (this according to the intensity of the glacial phase); and steppes and semi-deserts spread over the country. The rivers, suffering from an insufficient water supply, accumulated their loads mainly in their middle courses, the transporting powers of the water being inadequate as compared with the enormous quantities of waste prepared by frost weathering. . . .

When, after the climax of the glacial phase, warmer and more humid conditions returned, the quantity of water carried by the rivers increased once more, and denser vegetation spread over the country, gradually hindering superficial denudation. The rivers resumed their work of cutting and formed the actual terrace out of the accumulated beds of gravels.[33]

That some valley deepening must take place independently of any climatic change during the long stage of maturity in an uninterrupted cycle may be deduced from the assumption that the land around the headwaters of a river must eventually be worn down by long-continued denudation. This is generally a slow process, however, and it is questionable whether any terracing may be expected to occur as a result, except perhaps in rare and exceptional cases. Weakening of gradients of graded rivers during the stage of maturity has been taken into account by Davis, who notes also that such degradation may be interrupted by a temporary phase of aggradation (p. 81). In the general case this degradation is pictured by Davis as too slow to leave terraces. Even after an aggradational episode, when the river cuts down again it "will slowly wear away the flood-plain deposits; yet in so doing it will not terrace them, because their surface will be worn *pari passu* with the slow wearing down of the entire valley floor.[15]" A slightly different opinion has

Fig. 174. Submaturely dissected terraces on both sides of the Makara Valley, near Wellington, New Zealand.

been expressed by Russell,[27] namely that terraces might in such a case be formed, but that the "processes of terrace-making are slow and the topographic forms resulting may be greatly modified or even obliterated by subsequent denudation as fast as they appear".

A belief that some features to which a cyclic origin has been ascribed—besides many obviously non-cyclic terraces—are in reality normal features of an uninterrupted cycle seems to permeate the writings of Douglas Johnson, whose influence may be seen in Lobeck's discussion of terraced fans.[22] In order to account thus for the abandonment of terraces during the course of secular denudation it appears to be necessary to postulate the occurrence of surges in the rate of erosion that are difficult or impossible to explain except on the hypothesis of climatic changes. Otherwise this theory of terracing seems open to the same objections as Walther Penck's discredited theory of intermittent erosion during continuous upheaval which will be discussed in Chapter XIX. Challinor[7] has pointed out, however, that lowering of local base-levels produced by some normal developmental changes in the graded profiles of trunk streams may well be of such magnitude as to cause distinct and perhaps conspicuous terracing in tributary valleys and even in some cases in the upper reaches of main valleys.

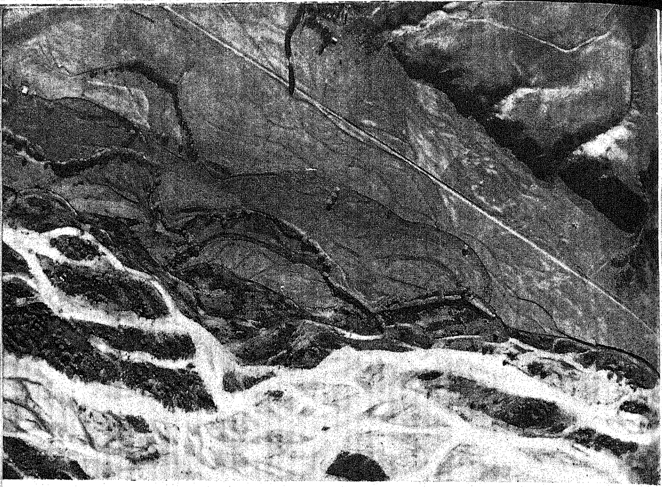


Photo from N.Z. Aerial Mapping Ltd.

Fig. 175. Terrace on the north bank of the Waitaki River, New Zealand, which preserves on the surface a braided pattern of ancient channels. The fronts of this and of lower terraces are scalloped by "meander" scars.

Correlation of Terraces

From the foregoing considerations it will be clear that the correlation of terraces—even of well-marked valley-plain terraces—from one valley or valley system to another, or even in reaches of the same valley that are separated by gorges, may be a matter of uncertainty, and may even present insuperable difficulties. Far inland, for example, it will be very unlikely that surges of vertical corrasion resulting from regional elevation or eustatic emergence will have worked their way an equal distance upstream in different valleys, while the effects of warping and tilting of the surface are necessarily local and sporadic; and so a fair degree of agreement of terrace patterns, if found in separate valleys, points to a climatic as the only probable general cause of terracing.[1]

Slopes of Terraces

The slopes of terrace surfaces, or treads, may be considered both transversely to the river and longitudinally. Transversely to the

valley-direction terrace treads are initially the surfaces of former flood plains, but may be more or less maturely dissected (Fig. 174). Where they have escaped dissection they are broadly level but may still preserve the irregularities of flood-plain surfaces, viz. "bars and swales, abandoned channels, natural levees . . . , meander scars, and minor depositional features."[28] Braided patterns of former channels like those in which water now flows at a lower level are seen in Fig. 175 on a terrace relic of an aggraded plain. Traces of cut-off meanders are found especially at the rear of a terrace along the base of the concave embayment in the front of the next higher terrace, where the last swing of the former river channel was cut off and abandoned.[14] On certain terraces, on the other hand, especially in mountainous and semi-arid regions, and especially on the highest terrace (Fig. 159), there is a thick cover head of alluvial gravel in the form of fans spread by tributary streams, as has been noted in the case of the terraces of the Shoshone River, in Wyoming.[21, 23] Such fans may be confluent with talus slopes from a high valley side between tributaries, so that all parts of the terrace surfaces have strong across-valley slopes. Instead of fans and ordinary talus material, or incorporated with these, there may be "head" (in the strict sense) that has been carried and spread by periglacial solifluction. Similar talus and alluvial accumulations on marine terraces have been termed "cover head" by Davis. These sloping surfaces, though they are found on terraces, are really valley-plain features, and were present in some cases before valley plains were reduced to terraces. They imply, however, that lateral planation on what is now the terrace has long been ineffective, and this condition dates generally from the incision of the valley to a lower level.

In the case of terraces with thick cover head observation of the height of the surface is of little value as an indication of the depth to which a river valley has been deepened in the process of terrace cutting; but the former level of the river may be revealed by exposure of the river-bed or valley-plain deposits beneath the cover head in a section on a terrace front[21] or in some dissecting ravine (Fig. 176, *A*).

Some terraces, termed "catenary" by Hanson-Lowe,[19] which slope towards the river, do not carry any flood-plain deposits such as will indicate a former river level. They have become terraces as a result of lateral corrasion, and perhaps without any contemporaneous

deepening of the valley (Fig. 176, *B*), when a vigorous stream has undercut the toe of a broadly concave valley-side slope or valley-floor side strip (see Chapter XIV). In China especially the concave portion of lower valley-side profiles is very broadly developed and pediment-like in the larger valleys, which have been long in existence and are floored with extensive alluvial, air-borne, and colluvial, or slope-wash, deposits; and thus catenary terraces are common, as Barbour,[1] Hanson-Lowe,[19] and Whittington[31] have observed.

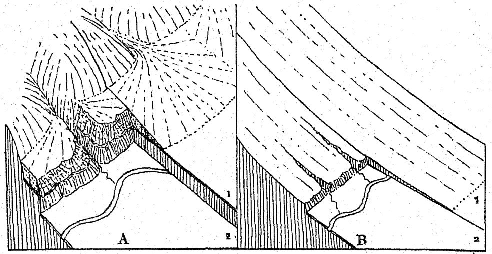


Fig. 176. Development of sloping terraces of variable and indefinite height. *A*: The Shoshone type of terrace, with thick alluvial cover head over a definite flood plain that marks a former level of the river. *B*: The "catenary" or Yangtze type of terrace (with no definite rear boundary) developed in a widely open valley by lateral corrasion alone.

It is improbable that any terrace treads that are cut as flood plains are developed with appreciable across-valley slope, though it has been suggested deductively that this will be the rule.[22] In the case where a slowly degrading meander belt is swinging over towards a valley side in the process of cutting meander-scar terraces it leaves behind it a succession of low but level-topped terraces of the slip-off slope variety, but most of the terraced slip-off slopes so formed are subsequently destroyed by further swinging (Fig. 177).

Apart from irregularity introduced by partial dissection, by initial flood-plain diversity, and by the presence of cover head of varying thickness, longitudinal terrace profiles slope generally in the same direction as the gradients at which rivers flow below them, as they have been in general determined by the same rivers at the time

the terraces were parts of their valley floors. Tentative correlation of remnants of valley floors preserved as terraces in the valleys of southern England has led to the conclusion that the profiles of the graded river gradients at which the valley floors were developed approximate to certain simple logarithmic curves. Green,[18] who has made the investigation, admits that the correlation of terraces on

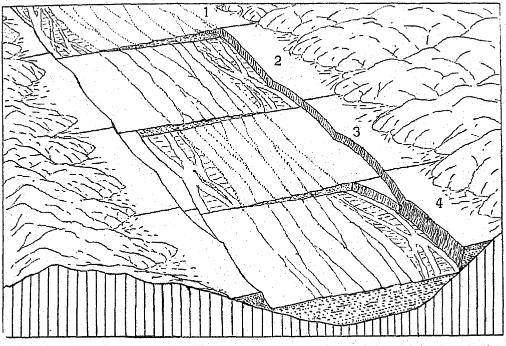


Fig. 177. Development of terraced slip-off across-valley slopes and the progressive destruction of these during successive stages, 1-4, of terrace-cutting.

which the generalisation is based has been somewhat influenced by the working hypothesis itself, but he has shown that the method of fitting terrace remnants to a calculated curve of graded stream profile, if used with discretion, is of value in correlation in cases where precisely levelled altitudes of points on the former flood plains are available in a region not affected by warping.

It is not to be expected that longitudinal terrace profiles and present-day river gradients will be strictly parallel. Especially in the less stable crustal regions it is reasonable to suppose that gentle warping of the land surface will have steepened, weakened, and even reversed the original down-valley slopes of some terraces. If no warping at all has taken place, however, a terrace may be either less steep than the present-day river gradient, where the

inner valley has been cut as a result of lowering of base-level and is still young, or steeper, as may be expected where the surges of erosion that have caused terracing have resulted from climatic fluctuation during the general lowering of the land surface by denudation. Terraces of this latter kind may indeed be expected to converge on sea-level at a river mouth, as terraces very often do, though not necessarily in all cases for the same reason. This is the arrangement termed by Briquet[3] "discordant" and contrasted by him with the "concordant" arrangement, which is characterised by downstream divergence of successively developed valley-plain profiles such as may perhaps be expected if intermittent regional emergence has taken place at diminishing intervals of time, so that successive graded stream profiles are less fully mature than their predecessors and so are progressively steeper. Even if each successively cut inner valley becomes fully mature, it may well be that as a valley as a whole becomes deeper the river in it has waste in greater quantity (and coarser) to remove, and that, therefore, its profile when graded will be steeper. This is, indeed, a recognised principle.[2] Further reference to the reconstruction by terrace correlation of former profiles of rivers will be made in Chapter XIX.

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CHAPTER XIV

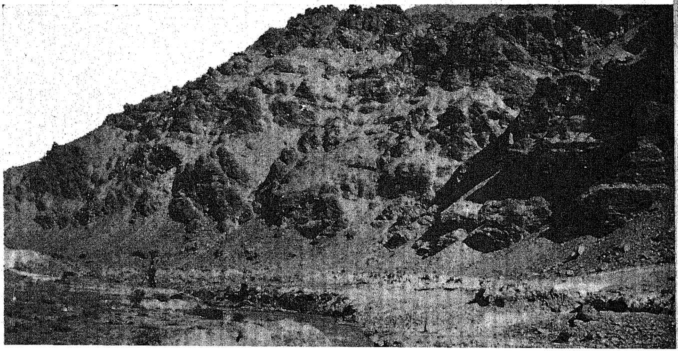
Maturity of the Landscape; Subdued Relief Forms

ON THE SIDES OF YOUNG VALLEYS AND GORGES AND ON THE FACES OF escarpments, where slopes are steep, waste is removed as rapidly as it is produced by weathering, the waste mantle is thin, and there are many outcrops of bare rock, generally of jagged and irregular form, so that the slope is not only steep but uneven. It may be broken by more or less irregular structural terraces, where heterogeneous strata outcrop. Such slopes are analogous to the uneven profiles of young rivers, and, like them, they may be described as not yet graded (Figs. 178, 179, 225).

GRADING OF SLOPES

Later, when rivers are no longer cutting downward so as to undercut the slopes, valley-sides are worn back to gentler declivities.

Fig. 178. Rugged slopes, not yet graded, Dunstan Gorge of the Clutha River, New Zealand.



As weathering, creep, sliding, and streaming down of waste continue, outcrops of bare rock are gradually replaced by slopes of waste. These are at first short, discontinuous, and broken by rock outcrops, but outcrops are weathered away, and the waste slopes become *graded*[11] in a manner somewhat like the grading of a water stream, though the gradient of a waste stream when it is graded is necessarily very much steeper than that of a water stream because of the relative immobility of the material of which it is composed and the greater retardation of its flow by friction. In this way are developed the smooth hillside slopes of full and late maturity (Figs. 179, 180).

Much steeper slopes become waste-covered and smoothly graded under the protection of a forest covering than under more open or discontinuous vegetation. In New Zealand, especially in the northern part of the country, and in many other regions also, though these are for the most part intertropical, the virgin forest consists of large trees together with a dense undergrowth, and this affords the ground beneath it complete protection from raindrop impact.

The forest and its attendant litter layers absorb much rainfall. Thus the run-off is low and so impeded that it has little power to erode. The roots of forest trees anchor together the soil and subsoil. On the steeper hillsides the curiously curved lower trunks of trees, with their deeper roots trailing uphill, evidence the forest's effort to remain anchored, and the forces tending towards the downhill creep of the soil (Taylor).[30]

Though creep is thus active, more rapid mass movements seem even more effective in the downhill transfer of waste. "Everywhere throughout the forest hill lands arcuate scarps indicate the sites of former slips". The whole process of downhill migration is slow, however; "ground bared by slips has time to be invaded by vegetation before another slip appears; bare rock has time to weather";[30] and under such conditions of retarded erosion and soil accumulation very steep slopes become graded.

Feral and Subdued Summit Forms

When the dissected landscape first enters on the stage of maturity, the crestlines of ridges and spurs are formed by the intersection of valley sides that are for the most part still steep, so that the ridges

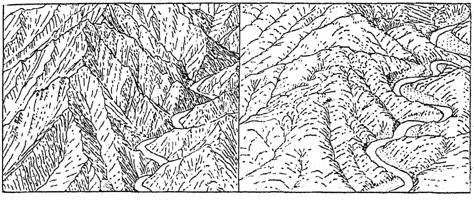


Fig. 179. At left, a landscape feral in early maturity, compared with the same landscape (at right) subdued in full maturity. (After diagrams by W. M. Davis.)

are sharp and their crests are uneven. They may be described as *feral* (Fig. 179, 179A). Later, however, spurs, ridges, and peaks become less sharp. In a terrain of homogeneous rocks the rounding of crests takes place first where relief is small, and in the case of mountain dissection this is on the flanks and among the foothills of the

Fig. 179A. Feral landscape with rather fine texture of dissection. Part of the northwest slope of the Kaikoura Range, New Zealand, which is the dissected back slope of a tilted block (p. 313). *V. C. Browne, photo*

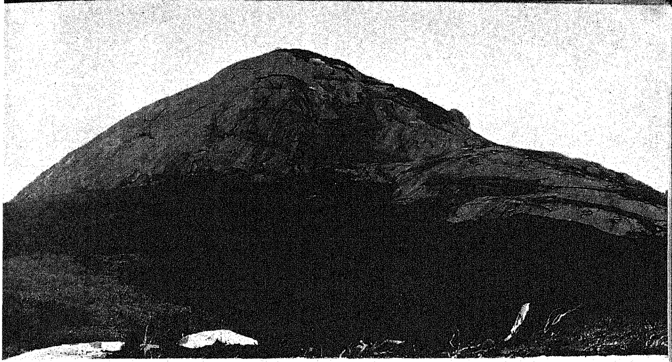
V. C. Browne, photo

Fig. 180. Medium to fine texture of dissection on foothills of the Tararua Range, near Wellington, New Zealand. The rocks are greywacke somewhat deeply mantled with residual clay. The summits are of subdued form.

mountains (see Figs. 261 and 283, Two Thumb Range, New Zealand); but higher ridges eventually lose their sharpness also as they are lowered by erosion. When the slopes have become moderately gentle, broadly convex hills and mountains have been shaped, which Davis[11] has described as *subdued*. Soft-rock areas are early reduced to subdued forms, though outcrops of resistant rocks near them may still remain rugged. When the majority of salient forms are subdued the landscape passes from early to full or late maturity (Fig. 179, 180).

Texture of Dissection

Landscape forms at the mature stage are distinguished as of *coarse* or *fine texture*. Texture is coarse, medium, or fine according to the spacing of the ravines or gullies that separate the minor spurs of a maturely dissected surface. Texture as so defined is not the same thing as "texture of drainage".[10] This latter, as defined, depends on the spacing of major valleys, which cut deeply and determine a measure of major relief. Between such major valleys there may be innumerable ravines and spurs or small hills, however, especially on a landscape with fine texture (Figs. 179A, 180). The more important



L. Cockayne, photo

Fig. 181. Monolithic dome on a granite terrain, Stewart Island, New Zealand.

the part taken by creep in the disposal of the weathered waste on slopes, conditioned by permeability of the terrain more than by any other single control, the coarser generally is the texture. An impermeable terrain may be gullied by rain-wash with development of a texture so fine as even to approach that of badland erosion.

Monolithic Domes

The subdued and broadly convex summit forms that have been described above are those of normally developed, mature, soil-covered landscapes. Under certain special conditions of weathering that affect granite and other massive crystalline rock bodies in which there are few joints some very large bare-rock domes are formed, which may be called "monoliths",[7] or *monolithic domes* (Fig. 181). They have been developed from initial forms with presumably rugged outlines by a process of large-scale exfoliation taking place in the main probably as a phase of weathering in which hydration of feldspars is important. The explanation of convexity of summit forms that fits these is, however, obviously not of general application. Stone Mountain, Georgia, is a well known example of a monolithic dome. Those of the Sierra Nevada of California have been described by Gilbert,[18] and those of Brazil (Fig. 182) by Branner[2] and others.*

* For further discussion of monolithic domes see *Climatic Accidents in Landscape-making*, a sequel to this volume.

Convex Landscape Profiles

The actual processes involved in the development of ordinary convex summit forms are not thoroughly understood, but there must be in operation some agency or agencies working in a manner different from the general processes of grading valley sides and of reduction of such graded slopes of waste to gentler declivities incidentally to the wasting away of the land surface as a whole. This must be the case, at any rate, if all graded valley-side slopes and all

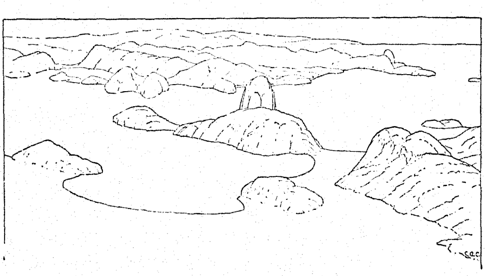


Fig. 182. Monolithic domes and sugarloaves of exfoliation, Bay of Rio de Janeiro. (Drawn from a photograph.)

slopes resulting from rain-wash transportation assume concave profiles, as Gilbert[17] believed to be the case from analogy with graded profiles of rivers; for divides, or ridge crests, formed by the intersections of concave slopes, however gentle the slopes may become, must remain angular and quite unlike the familiar convexly rounded forms of most hilltops and ridge crests.

A suggestion of Davis,[10] accepted and elaborated by Gilbert,[19] in explanation of the convexity of ridge crests is that this results from dominance of soil creep over other transporting agencies in the process of lowering the land surface by removing the waste mantle produced by weathering on and in the vicinity of divides. For the purpose of developing this hypothesis it may be assumed that soil creep acts alone—that is, unaided by rain-wash, etc.—in removing

a surface layer from the crest of a ridge or the top of a hill. The amounts of material so creeping past given points increase progressively with the distances of the points from the crest or summit. Thus slopes of increasing steepness in both or all directions from a horizontal summit are required, and will be developed, to facilitate transportation by creep. (Compare chalk escarpment slopes, p. 228.)

Soil creep rarely acts alone, however, and on some convex summits the soils are very thin and there is no evidence that effective creep is in progress. It seems very doubtful, therefore, whether creep is always the most important factor in rounding summits, and Lawson[22] concludes that the chief agent lowering many hilltops is rain-wash running off the surface during heavy rain, when the soil is saturated, as a "film" or shallow sheetflood, or a "network of rills" not yet concentrated or collected into definite channels. Such unconcentrated rain-wash and its effects are termed also "sheet-wash",[26] "rill wash",[15] and "sheet erosion".[28] Lawson regards the process as merely transportation, without corrasion, and a necessary preliminary is complete rock decay, which produces fine soil particles suitable for transportation by this agency. In contrast with water flowing as streams in definite channels, where the moving water is "underloaded" and for this reason corrades and develops the characteristic concave stream profile, the film, or shallow sheetflood, "is continually loaded to capacity for the grade of material available". It "is always in contact with its load, and the latter is at all points free and ready to be picked up or moved". The fully loaded condition prevents corrasion, such as would lead to the development of gullies.[22]

A characteristic feature of valley-side profiles of youth and very early maturity, before summit convexity appears, is a straight slope (rock material being assumed homogeneous). At first the straight slope is too steep to retain a mantle of weathered waste, or soil; but when deepening of adjacent valleys ceases, such slopes become less steep, and carry a layer of residual soil of progressively increasing thickness. Razor-back divides and pyramidal peaks now have their sharp angles and points replaced by convex forms, which gradually become broader and more extensive. The summits acquire "curvature of greater and greater radius. . . . The maximum lowering of the surface of the hill, measured in the direction of the vertical, is at the summit, where, paradoxically, the volume of water, the agent

of erosion, and also its velocity, are always at a minimum".[22] At the same time what remains of the earlier straight slope (tangent to the summit curvature) recedes either (as Lawson assumes) parallel to itself or with diminishing declivity, and, sooner or later, concave lower valley-side profiles also gradually replace the earlier straight slopes until a profile that is a compound curve, convex above and concave below, has been developed, which is characteristic of full and late maturity.

Uniformity of rock character in the terrain has been assumed in the foregoing discussion of slope forms, but is not generally found in nature. The case may be complicated by juxtaposition or alternation of relatively weak and resistant rocks or of rocks of different permeability. At a rock-formation boundary the point of inversion from convexity to concavity of slope on a valley side may ascend or descend. Even small differences produce considerable results, and thus hillside slopes exhibit infinite variety of form.

Concave Valley Sides

Beneath the surface in the concave lower slopes when they first develop tangent to an early position of the remnant of the primitive straight slope there is some soil washed down from above, which has accumulated as a fringe of small fans and talus slopes, but these lower slopes are, in the main, slopes of transportation rather than of accumulation when valleys have become fully mature, and their soil is derived in part from "local subsoil weathering".[15] Their concavity (diminishing declivity down the slope) is ascribed by Davis[15] and others to progressively increasing fineness of the grade of waste on them down the slope, which is a result of progressive weathering during its gradual downhill transportation. In late maturity the lower, concave valley sides are reduced to gentler slopes and become side strips of the valley floors.

When valley plains have become broad relatively to river size, their further expansion by lateral planation under normal humid climatic conditions generally becomes extremely slow, as the river in its meandering course then swings more and more rarely against bedrock in the valley sides. The stage at which steep bluffs bordering a flood plain have testified to its rapid lateral growth is long past. The last traces of bluffs are fading out of the landscape, and it is obvious that lateral stream corrasion, though it cannot be said to

cease, assume a minor rôle. The general denudational lowering and grading of the land surface, always in progress, becomes now of relatively greater importance, especially in its function of developing very gently sloping valley-side profiles that take the place of the bluffs of an earlier stage. At the stage of late maturity of transverse profile, the middle portion of the valley thus assumes a catenary, or very broad U, form (Fig. 183).

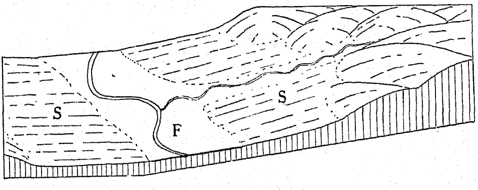


Fig. 183. An advanced stage of valley-floor widening in late maturity. *F*, flood plain; *S*, valley-floor side strips. (Based on a diagram by W. M. Davis.)

The continued removal of the finer soil from the valley-side slopes causes them to recede from the banks of the graded stream to which they previously descended; and as they do so narrow strips of valley floor . . . will be developed at their base, back of whatever flood plain . . . is simultaneously formed by the stream. As these slopes widen, the concavity of the profile across the valley bottom . . . is given broader expression. . . . The lateral strips will be everywhere covered by detritus, partly derived from local subsoil weathering, partly washed down from the valley sides; and the detrital cover will, in time, constitute a large part of the valley floor. . . . Each lateral strip of the valley floor will have . . . a . . . transverse slope from the valley side toward the stream or its flood plain, so that fine soil washed down from the valley side can be transported across the strip by the agencies, rill wash chiefly, available for that duty. (Davis).[15]

Notwithstanding the fact that lateral corrasion by the river will usually continue to widen the flood plain by cutting back the lower edges of the valley-floor side strips, these "will be developed [at the expense of the upper valley-side slopes] to greater and greater width independent of the flood plain".[15]

In time valley-floor side strips develop in tributary as well as in main valleys. They encroach more and more on the dissected interfluvial areas, and eventually coalesce to form a great part of the peneplain that takes form in the old-age stage of the landscape cycle as residual salients waste away to smaller and smaller dimensions.

The level on the valley side at which the concave curve of the valley-floor side strips merges into the upper, or ridge-crest convexity at full maturity is determined by that at which waste that is subject to continued weathering as it is carried down the slope reaches a certain degree of fineness. The debris of weathering on the higher parts of the convex slopes is relatively coarse, and transportation of such material both by wash and creep as it increases in quantity downhill requires a steepening declivity downhill, i.e. convexity of slope. As it is reduced gradually by weathering to a finer texture and becomes less permeable, though increasing still in quantity, it can be transported (mainly by wash) down a slope of increasingly gentler declivity, i.e. with a concave profile.[26]

The proportions of convexly rounded crests and concave lower slopes in mature landscapes vary very widely, but in regions of temperate climate, if the nature of the rocks favours deep weathering and the rainfall and temperature are such as to encourage dense forest growth, very broadly convex (subdued) forms dominate the landscape.

Razor-back, or Knife-edge, Ridges

Wherever rock composition and texture and other weathering conditions do not conduce to the formation and accumulation of thick soil or lead to the early production of much fine waste, or the soil is not protected by close growth of vegetation, so that it is subject to excessive sheet erosion, late survival into the mature landscape of rather sharp-edged dividing ridges is favoured, though even these generally develop some small measure of rounded convexity at the crestline (Fig. 179A).

The sharpest, or razor-back, forms are found in hot and wet regions, however, and more especially where basaltic volcanic rocks form the terrain. On these chemical weathering decays the rock material to a considerable depth, and rain-wash scours away the soluble and the fine-grained products of weathering from exposed rock surfaces.

In torrid lands of rapid weathering and heavy rainfall the ridges that rise between broadly opened valleys are so extraordinarily sharp that, in proportion to their breadth, they realise the knife-edge acuteness which Gilbert believed ought to result from degradation by running water; and the meaning of their sharpening appears to be that, under the extra heavy rainfall they receive, they really are sharpened chiefly by running water rather than by soil creep, in spite of the rapidity with which soil is there produced (Davis).[14]

According to Lawson[22] excessive rainfall is the determining factor. "If the rain-wash be excessive, the soil is removed, or does not form, and the conditions are then those which characterise degradation in wet climates as distinguished from humid climates" [in which convexity of summits is developed].

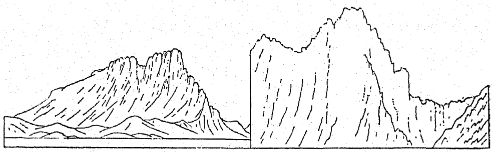


Fig. 184. Razor-back ridges in the Society Islands. Left, part of the island of Borabora (after Davis); right, Dana's sketch of Mt Orohena, Tahiti.

Examples of very sharp razor-back ridges separated by broad valleys with concave side slopes occur commonly in dissected volcanic islands of basalt in the tropical seas, notably in such islands in the Hawaiian and Society groups (Fig. 184). Perhaps the most conspicuous of the sharp divides are those of Raiatea, where one such arête has attained such thinness that a window has developed in it. In Tahiti, as described by Dana,[9]

the larger . . . valleys abut at their heads against the central peaks in lofty precipices—precipices of two to nearly four thousand feet. Some of the larger valleys are widest at the centre of the island and terminated under the peaks in vast amphitheatres. The ridges . . . are . . . very narrow. Above an elevation of 3000 feet or so (as I found in my ascent), the top edge of the ridges for much of the way is but three or four feet wide . . . ; and in some spots it diminishes to a foot, and even, at times, to a thin edge of bare rock;

and from the crest the declivities either side pitch off steeply 1000-2000 feet.

Marshall[22a] also, in his description of Moorea, refers to "the piercing shape of the aiguilles" and to "steeple-shaped peaks separated by the most profound valleys with sides so steep that they cannot be scaled."

"Oahu" Valleys

This kind of ridge-and-valley profile has been observed and studied in detail in Oahu, Hawaiian Islands (Fig. 185), where Stearns[29] has found valley heads of amphitheatre form and precipitous valley walls retreating without appreciable reduction of steepness in the massive piles of partly weathered lava sheets of which the mountains are composed.[8] Retreat of the nearly vertical walls of the valley heads especially is greatly accelerated by plunge-pool erosion (Fig. 32) at the many points where abstracted consequent streams enter a master valley as tributaries (compare Fig. 61), and narrow spurs left standing between the plunge pools "fail by their own weight" (Stearns)[29] and collapse as rockfalls or slides. Another observer, Wentworth,[31] has attributed considerable importance to the unusually great depth of the water table, which is a result of the porous nature of the volcanic rocks. The whole of the surface undergoing erosion in the mountainous parts of the islands is, indeed, far above the water table, and is thus weakened by chemical weathering.

The combination of tropical weathering conditions with initial mountain forms built of porous basaltic rocks (resulting in a water table far below the surface) is obviously a special case favouring the development of broadly concave valley profiles with the side walls, as well as the amphitheatre heads (Fig. 32), retreating without change of slope (Fig. 188) and sharpening the ridges. In a post-mature stage the ridges are destroyed and the land surface is reduced to small relief, such as has developed, mainly as a result of this erosional process, along the whole windward (north-east) side of the island of Oahu[29] (Fig. 76).

Plateau Margins

Some authors have directed attention in particular to the profiles of the slopes bordering valleys that are incised in elevated plains or

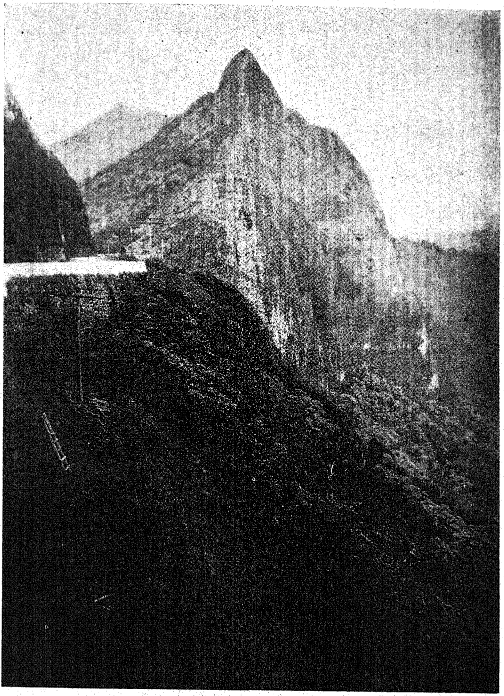


Fig. 185. Sharp divide at the "Pali", near Honolulu, Oahu Island, Hawaii.

plateaux. The edge or shoulder between the plateau and the valley side generally shows a certain amount of rounded convexity, and the rounding has developed presumably as a replacement of a sharp edge present at an infantile stage of development. The familiar

argument that such rounding of an edge is the effect of weathering proceeding from two sides is rejected as an explanation in this case by Bryan,[4] who points out that the rate of erosion on the horizontal (plateau) facet must be relatively so slow as to be negligible. Recalling a deductive argument of Bain that erosion by running water will develop a profile convex to the sky if not controlled by a base-level, Chamberlin and Salisbury[6] point out that there is normally a slight residual convexity even at the head of the graded longitudinal profile of a river. They explain the convexity of upper valley-side slopes by applying the same principle; and "since the side slopes of a valley are much shorter than its lengthwise slope, a larger proportion remains convex". In Bain's deduction (referred to above)

> he arrives at the condition of convexity by starting . . . with . . . a block of country with flat top and vertical sides and allowing weathering, sheet erosion, and stream erosion (stream action may be considered as merely a special case of sheet erosion, as he remarks) to act in the first place along a horizontal edge (Challinor).[5]

Escarpment Profiles

An important case is that of the profiles of structural escarpments such as are especially abundant in dissected plateaux consisting of rocks with horizontal structure. King and Fair,[21] closely following Wood,[33] recognise four distinct elements (Fig. 186) in the profile of an escarpment:

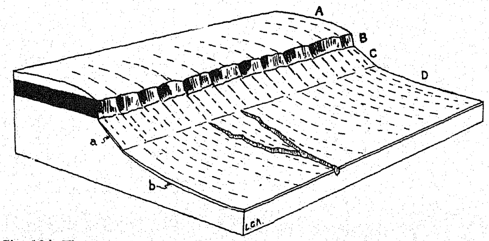


Fig. 186. The slope elements on a valley-side escarpment. *A*, convex slope; *B*, free face; *C*, constant slope; *D*, concave slope; (*a*) talus; (*b*) soil. A "slope donga" developed by gullying due to abnormally accelerated erosion is shown also. (Drawn by L. C. King.)

(*a*) the upper or *waxing slope* [or convex slope] steepening downwards; (*b*) the *free face* or outcrop of bare rock; (*c*) the *constant* or detrital slope, sometimes called the *gravity slope* [compare Meyerhoff[23]]; and (*d*) the *waning slope* [or concave slope] flattening towards the valley.

It is advisable to replace "waxing" and "waning" by the noncommittal terms "convex" and "concave" respectively to avoid an appearance of premature acceptance of W. Penck's views (to be outlined later in this chapter) regarding the origin and development of the slopes to which they are applied.

The waxing [convex] slope often steepens at the edge as retreat continues; the free face tends frequently to disappear, when the hill presents a grassy slope unbroken by rock outcrops [i.e. a graded slope]; the constant slope, being composed of detritus which has come to rest at its angle of repose, retreats parallel to itself, i.e. at a constant angle of slope; the waning [concave] slope ["wash slope" of Meyerhoff[23]] . . . is gently concave upwards (the curve of water erosion be it noted) and alters (*a*) by progressive flattening as the transported waste upon it becomes finer, and (*b*) by growth hillwards at the expense of the constant slope as the hillside retreats. . . . [The concave slope] is a product largely of sheetflow, which distributes the soil particles outward from the hill mass. Below the soil lies a solid-rock basement the top of which has a similar curve to the waning [concave] slope. (King and Fair.)[21]

The concave slopes fringing great escarpments (for example, the Book Cliffs escarpment, Utah, as described and figured by Rich[26]) assume the dimensions of extensive pediments. Where crossed by streams these are subject to some dissection in the course of their gradual development, which leads to irregular changes in the surface form, with perhaps some terracing and isolation of low mesas, as Rich[26] has described.

Walther Penck,[25] though he regarded concave slopes as a whole as unbroken curves (on terrain with homogeneous structure), distinguished the steep upper part as the *Steilwand,* terming the gentler slope below this the *Haldenhang,* this being succeeded by a very nearly level *Subhaldenhang.* The last is closely analogous with the "valley-floor side strip" of Davis (Fig. 183). These terms are applied to the elements of slopes in general—not to escarpment slopes only.

Chalk Escarpments

The escarpments of the chalk in the downs of south-eastern England present a very broadly rounded, or subdued, convex profile, unlike many escarpments in which a cliff-like free face is prominent on the outcrop of the cap rock. Baulig[1] attributes the convex form of chalk slopes to the porosity of this cap rock. Where less permeable rock is present under the chalk, it has been shown that the point of inversion on the compound curve of the slope profile is found at the base of the chalk stratum. Above that line porosity prevents run-off, and the chalk slope therefore affords a perfect example of a convex profile produced by soil creep acting practically alone.

Mature-born Landscape Forms

The explanation of compound (convex-and-concave) landscape profiles in general as mature forms implies that such profiles are, or, at any rate, may be, derived by normal processes from characteristically young profiles in the course of a cycle of erosion. It is sometimes maintained, however, that the assumption of such a history for them is not in accordance with facts. It is, indeed, probable that some similar profiles have been developed without their passing through an anterior condition typically young; and such may be described in a Davisian phrase as "mature-born".[13] Their inclusion in the cycle scheme presents no difficulties; but a special case must be envisaged in which elision of the stage of youth takes place. To explain the forms of youth, i.e. to deduce the development of forms to match those regarded as young in natural landscapes, it is generally convenient to assume that, as a result either of the resistant nature of the rock material to be eroded or of the rapidity of the uplift introducing erosion, the amount of erosion taking place *during* the initial uplift is relatively so unimportant that it may be neglected as compared with the erosion that follows completion of the uplift. Such an assumption is unwarranted, however, when erosion is working on very weak materials or when uplift takes place very slowly. In either of these cases complete elision of the stage of youth in the landscape cycle may be expected to occur, or, at any rate, profound modification of the typical forms of youth must take place.

The preglacial landforms of the European Alps, as they have been postulated by Albrecht Penck,[24] may be taken as typical of a mature-born landscape.[14] This region exhibited a considerable degree of accordance of summit levels (Chapter XVI), the so-called *Gipfelflur,* an explanation of which is deduced by Penck as follows. A ridge-and-valley surface of considerable relief (mature-born) develops during preliminary uplift. Uplift continues at a uniform rate, and during its progress the rivers are constantly reinvigorated, so that they continue to cut down through the rising land mass. Development of a stable and characteristic valley-side slope now induces a condition of constant relief, in which valley deepening and ridge lowering continue at the same rate, though for a time the land mass as a whole rises at such a rate that absolute altitudes continue to increase. Maturity persists in the mature-born landscape.

Next, according to Penck's deduction, the rivers, constantly invigorated as they are carried higher and higher above sea-level, must cut downward more and more rapidly. Without change of characteristic ridge-and-valley forms and slopes, or of relief, there will now be an approach to a stable condition, in which the lowering of the whole surface by erosion just keeps pace with the uplift of the land; so that an apparently unchanging, though in reality continually eroded, landscape exists for an indefinite period.

Such an accident of uplift at a rate neither too slow nor too rapid may, therefore, introduce a phase of stability of landscape forms that will temporarily interrupt the continuous sequence of changes envisaged in the presentation of the ideal cycle. The delicate adjustment that must be assumed makes this necessarily an exceptional case, but the analysis will serve to remind the reader of the infinite variety of nature.

A hypothetical case involving slower, though continuous, uplift has been analysed by Davis,[12] where "the stage of youth would have been elided and that of maturity would have prevailed from the beginning". Features of the landscape prevailing while uplift was in progress would be

> broadly open valleys, whose gently sloping evenly graded sides descend to the stream banks leaving no room for flood plains. . . . The absence of flood plains would show that the streams had not yet ceased deepening their valleys, and the graded valley sides would show that the downward corrasion by the streams has not been so

rapid that the relatively slow processes of slope grading could not keep pace with it (Davis).[12]

THE THEORY OF "WAXING" AND "WANING" DEVELOPMENT

Even though mature-born, convex-and-concave landscape forms have generally passed through later stages of their development after cessation of the initial uplift in the manner outlined in the early part of this chapter. An alternative deductive explanation of some such forms has, however, been proposed. Walther Penck[25] has explained hillside and valley-side features on the basis of an assumption that the development of mature landscape forms commonly accompanies (instead of following) the incision of valleys, which means that it takes place while uplift is still in progress. His explanation of the origin of combinations of convex and concave profiles assumes that the landscapes containing them have passed through successive phases of "waxing" and "waning" valley development, the former characterised by valley incision by vertical corrasion (due to uplift) taking place at an increasingly rapid rate, and the latter by a later slowing down and perhaps eventual cessation of the process (along with the uplift that has caused it).

From an analysis of straight-sloping valley sides of "uniform" development—i.e. development accompanying vertical incision at a uniform rate—in which V-shaped valleys are formed (steeper sided the more rapidly they are cut), a conclusion is reached that all uniformly sloping elements of land slopes, once they are developed, continue thereafter (in homogeneous rocks) to retreat from the valley axis in a direction perpendicular to themselves at rates depending on their steepness, the steeper slopes migrating back much more rapidly thus than those of gentle gradient. The argument for retreat of elements of compound slopes without altering in steepness is that, where any such element has below it one of greater or less declivity, the point at which the declivity changes is a local base-level for the element of the slope immediately above. From this hypothesis of retreat of each element of a slope in a direction at right angles to itself follows the argument that a stage of waxing development (accelerated incision) is recorded by the presence of convex valley-side slopes, and one of waning development (incision at a diminishing rate) by concave valley sides. Thus it is claimed that a valley side that is convex above and concave below has resulted from waxing followed by waning development of the valley.

It seems obvious that during slowly accelerated incision lower valley sides will generally become progressively steeper, but it cannot be claimed conversely that every valley-side convexity of profile proves that the valley it overlooks has been developed in an episode of accelerated downward corrasion. As regards valley-side concavity, this can be regarded as related to vertical incision of the valley at a diminishing rate only in so far as this means a virtual cessation of vertical corrasion, but such a condition usually is merely a matter of river grading and maturity. The relation can be accepted quite independently of the theory that all side slopes retreat without change of declivity. The assumption, on the other hand, that convexo-concave slopes are necessarily an indication that certain changes in the rate of an assumed progressive uplift have taken place during the development of a valley has been characterised by Johnson[20] as a "fantastic error". As we are warned by Baulig[1]:

> One should not ignore the obvious fact that convexity and concavity of slopes very often depend on lithology. Convex slopes are common on rocks yielding coarse, permeable debris, while concave slopes are more frequent on fine-grained, more or less impervious material. More than that: convex slopes on chalk, concave slopes on clay are often formed in the same portion of a valley, either beside or above one another. . . . But the radical error in this conception [Penck's] consists in believing that a graded valley-side is made up of a number of distinct elements *successively developed*. In fact a graded slope, like a graded river profile or any other profile of equilibrium, cannot exist and persist except through the action of *a loose mass* (in this case the debris) *in motion*; which amounts to saying that all parts of the profile are mutually dependent, all in constant though imperceptibly slow change, *all adjusted to present conditions and hence totally independent of past events.*

Slope Retreat

It may be pointed out that migration in their entirety of slopes of convex, concave, or compound form, if it can take place according to the law announced in the theory of Penck, can be a strictly horizontal retreat from the valley axis only if the rate at which each element of the slope migrates in a direction at right angles to itself varies as the sine of its angle of slope. Obviously, if the rate of retreat increases with the angle of slope more rapidly than the sine, changes of slope (convexities and concavities) will migrate upward

as well as outward from the valley axis, so that convexities will pass upward out of the landscape, which will eventually consist of broad concave valleys separated by angular divides. If, on the other hand, in any case the rate of slope retreat should increase with the declivity less rapidly than the sine of the slope angle, the theoretical migration of slope elements will be downward as well as outward, and convex forms will assume an increasing share of the landscape after the cessation of valley incision. Possibly investigation along this line will bridge the gap between the Davisian and Penckian conceptions of peneplain profiles (Figs. 187).

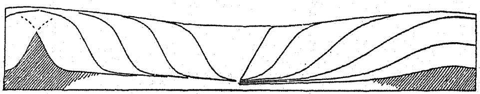


Fig. 187. Profiles of a widening valley; left, according to W. Penck; right, according to W. M. Davis. (After Davis.)

It seems very doubtful, however, whether Penck's simple generalisation of migrating slopes can be accepted. Each element of slope, considered as a straight slope, is a slope of transportation for material from above it. When smooth a slope may be regarded as analogous to the graded profile of a river in which a condition of equilibrium exists between gradient and load. Just as a graded river profile may become steeper or less steep with changing load, so, it would seem, may a hill slope, without change of local base-level. This argument is independent of the relation between the steepness of a slope and the texture (coarse or fine) of waste that can be transported down its declivity. Both diminishing load and increasing fineness of waste with progressive maturity of the landscape seem to require that in many cases an element of slope as it retreats in the course of landscape erosion *shall become less steep.*

If Penck's deduction could be adopted as a working hypothesis, it might afford an explanation of upper valley-side convexity in the valleys of main streams and some of their larger tributaries; but to attempt to apply this explanation to all surface convexities would be to imply that all streams, including minor tributaries and ultimate dissecting rivulets, had deepened and shaped their valleys

simultaneously, and that the entire pattern of streams in a landscape had been in existence throughout its dissection. This would be incompatible with any theory of progressive dissection of a land surface by insequent and subsequent streams.

On the hypothesis of strictly horizontal retreat of all slopes, as stated by Bryan,[4]

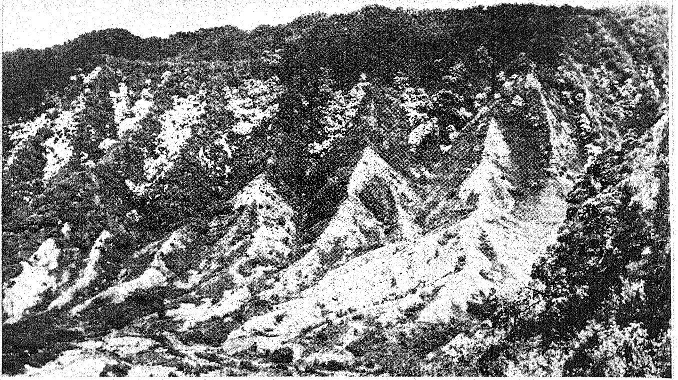
in the area between two parallel streams (the local base-level) the steep slopes from either side retreat until the original highland is consumed, and thereafter the divide is lowered and the relief of the area reduced [Fig. 187, left]. . . . [Eventually a peneplain (*Endrumpf,* Chapter XVI) will be produced as the result of such slope retreat.] Penck holds that steep slopes retreat without loss in their inclination and that steepness disappears only because the land above the grade of the *Haldenhänge* has been consumed. Gentle slopes replace steep slopes at the time when the *Haldenhänge* meet on the divides.

Observed Cases of Slope Retreat

Penck's explanation of slope retreat as "due to gravitational forces acting in a surface layer made mobile by weathering" has been described by Bryan[3] as an over-generalisation of the processes involved, and is regarded generally with disfavour. It is now widely recognised, nevertheless, that some processes of slope retreat are of great importance in shaping landscapes and in the general degradational lowering of the land surface. Back-wearing as contrasted with down-wearing of mountains is especially active in dry regions.* Even under humid conditions, however, Bryan[3] has found examples of slopes retreating as they are worn back by an erosive process he terms "gully gravure". Gullies are formed rapidly from time to time on a slope with a weathered surface, only to be choked again with debris and to have their places taken in the next gullying episode by other new gullies, with the general result that the scarp is worn back without necessarily any weakening of its slope. Such "gullying is recurrent in time but shifts laterally in space".[3]

Other methods of slope retreat are widening the valleys of basaltic island domes. In Oahu, as described by Wentworth,[32] some slopes, ribbed characteristically with sharp-edged spurs between

* For an account of landscape sculpture under arid and semi-arid conditions the reader is referred to *Climatic Accidents in Landscape-making,* a sequel to this volume.



Chester K. Wentworth, photo

Fig. 188. A retreating side slope in a valley dissecting a basalt dome, Oahu, Hawaii.

close-set fluting gullies, retreat as these gullies are cleaned out from time to time by landsliding of very wet soil, new soils being formed by weathering and held for the time by vegetation in the intervals between successive slides (Fig. 188).

Changing Relief throughout the Geomorphic Cycle

Changes in the relief of an eroded landscape may be briefly considered, attention being confined to the case of a landscape eroded during a single normal cycle in which initial uplift has been completed early, and in which no renewal of uplift has occurred to introduce complications. Relief, as measured by the depth of valleys below ridge crests, or, in youth of the landscape, below doabs or residual interfluves, increases while the rivers are young, i.e. as long as they go on corrading vertically. An exception to this rule is found, however, in the case of rivers that are so closely spaced that they dissect the land to maturity before using up the available relief (which must be great in most instances). Relief will remain of constant measure for a time while these rivers are not yet mature themselves though they have dissected the land to maturity.

When rivers become mature, relief has generally reached its maximum. If dissection of the upland has not been completed by

this time, relief will remain practically constant until landscape maturity has been reached, for the rate of further valley deepening will be negligible. Thenceforward, when the upper slopes of adjacent valley sides intersect in ridges, further valley erosion—which will result in widening scarcely, if at all, accompanied by deepening—will involve retreat of the valley sides and lowering of the ridge crests formed by their intersection (Fig. 187, right). Such lowering must be more rapid than any simultaneous valley deepening that may occur in the fully mature to senile stages of the cycle, and so in these later stages relief will continuously diminish. Any departure, of course, from the postulate of still-stand implies interruption of the cycle (Chapter XVIII), and the occurrence of any earth movement will eventually affect the relief.

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CHAPTER XV

Constructional Landforms

DURING THE COURSE OF A CYCLE OF EROSION SOME FEATURES ARE BUILT as a result of terrestrial accumulation of waste. These are of *constructional** origin, in contrast with those carved by erosion ("destructional"). Deposits of rivers, either in initial hollows of the land surface or in valleys cut by youthful streams and afterwards subject to aggradation, are, in general, less permanent than marine deposits, for they are laid down above the general base-level and are liable to be removed by erosion in the general lowering of the land surface that takes place in late maturity and old age of the cycle of erosion. Where still-stand does not continue while a cycle runs its full course, interrupting earth movements of subsidence may not only cause aggradation but also carry river-laid deposits below base-level, where they will be preserved indefinitely; but such deposits are buried, and, having no longer an exposed surface, are of interest only as geological formations and not as landforms. The shorter-lived deposits that remain above base-level, while they survive, present prominent and characteristic surface forms of great areal extent in some landscapes.

TALUS SLOPES

Among forms resulting from accumulation may be placed the nearly continuous mantle of residual surface waste, streaming, creeping, washing, and sliding downhill, and thus smoothing out irregularities of the surface, accumulating locally to fill hollows, and flowing around the more prominent rock outcrops until these eventually crumble and disappear and, the waste mantle being now continuous, the slope becomes graded. *Talus slopes,* or *screes,* are a phase of the waste mantle at its early, discontinuous stage (p. 16), being formed by the actual streaming, rolling, and glissading of rock fragments, generally newly broken by mechanical weathering and

* By Johnson and the Columbia school "constructional" has been used in a much more comprehensive sense than this. As a main head in classification the description "constructional" has been made to include forms of tectonic origin as well as those made by accumulation due to various causes.[14]

therefore unworn and angular. The surface slopes at the angle of repose[21] (p. 17), and the talus material accumulates in layers parallel with the present surface, but stratification is absent or very imperfect, as the material is quite unsorted.

Talus slopes are common features on mountain sides, where the fragments broken by mechanical weathering from bare-rock outcrops on peaks and high slopes stream down through funnel-like couloirs, or chimneys, of the disintegrating rocky surface. Confined thus for some distance, they spread out lower down in conical shape, delivering their surplus waste into streams of water that carry it away down the valleys. Talus slopes of this kind are particularly abundant among mountains that have been sharpened by glacial erosion, and they fringe the oversteepened sides of glaciated valleys in postglacial times, when these precipitous sides have become exposed to the weather, as, for example, in "the Screes", a vast, continuous talus apron along the side of the English lake Wastwater. There is widespread development of screes also on every slope of the rapidly crumbling Southern Alps of New Zealand, especially on their eastern slopes of greywacke, and in other parts of the South Island mountains where slopes have been recently steepened by glacial erosion (Fig. 189).

Fig. 189. Talus slopes and alluvial cones on glaciated mountain-sides in south-western New Zealand.

Talus slopes occur fringing cliffs, however these may have been formed, provided that the rate of removal of fallen debris from the base of the cliffs is not sufficiently rapid to prevent its accumulation there. Near Wellington, New Zealand, sea cliffs are not at present being undercut, for a small uplift has caused the shoreline to retreat from the cliff base. Since 1855, when the emergence took place, conspicuous screes have been formed of rock material that would in the normal course of events have been washed away by the sea as fast as it came down.

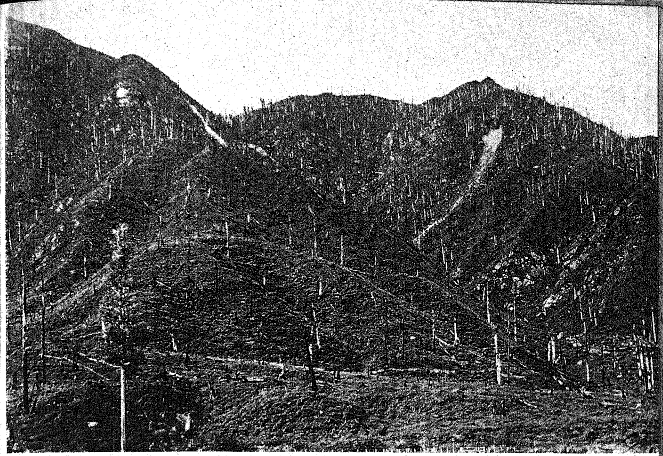
The angular fragments of broken rock forming the surface of a talus slope do not, as a rule, remain long enough in place to become weathered and allow of the formation of a soil covering, for the stream of rolling and glissading blocks from above continues, and so surface layers are either quickly buried as the thickness of the accumulation increases or else the surface is simply a chute down which fresh supplies of material continue to stream as it is swept away by running water at the toe of the slope. Vegetation is, therefore, generally absent from rapidly growing or vigorously "active" talus slopes. Where accumulation is slow enough, however, there may be a fairly close covering of forest or other vegetation.

Graded Land Slopes

On more gentle, graded slopes, where the waste mantle includes much chemically weathered waste and is not actively streaming downhill, vegetation flourishes. In fact, the stability of most of these slopes depends on the natural vegetation. A slope may be steep and yet the soil may be so bound together and protected by the vegetation, perhaps forest, that streaming and vigorous sheet wash, or sheet erosion, are prevented and only creep permitted, so that a state of balance has been arrived at between the rate of removal of waste and the rate of supply of new waste by weathering of the underlying rocks.

Reversion after Deforestation

When the natural vegetation, whether in a forested or a natural grassland region, is interfered with, erosion is revived on surfaces previously graded, with the formation first of debris slides (Fig. 190) and gullies (Fig. 191) and later perhaps the complete removal of the mantle of waste so as to leave bare rock. Especially in a land of



V. C. Browne, photo

Fig. 190. The forest cleared, debris-sliding begins, Matukituki Valley, New Zealand.

virgin forests, such as the greater part of the North Island of New Zealand was until towards the end of the nineteenth century, profound changes follow in the wake of land utilisation.

With the coming of the farmer forests are felled and burnt; the hillsides sown in grass, and thus begins the process of changing a forest soil into a grass soil. . . . The strong roots of the forest trees are replaced by the finer and generally shallower roots of the grasses. . . . Under the grass cover less rainfall is absorbed, causing increased run-off and wider fluctuations in the moisture-content of the soil. With more water passing over the surface of the soil sheet erosion becomes important wherever the soil is unprotected by vegetation. In dry periods the soil becomes more parched than it had normally done under forest cover, and cracking of the ground becomes more pronounced. The alternate wetting and drying of the soil, with its seasonal cracking and swelling, weakens the soil mantle and tends to speed up the processes of soil creep and slipping. Under the forest cover slipping was slowly taking place. Indeed, the shape of the hills themselves was due largely to the forest. However, a hillside in balance under forest is not necessarily in balance when clothed in grass. The soil tends to move into the valleys more

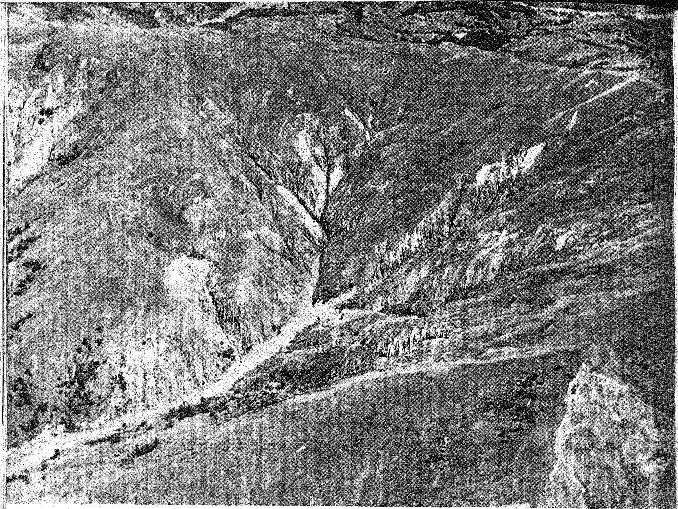


Photo from N.Z. Public Works Department

Fig. 191. Accelerated gullying in the Tarndale "slip", at the head of a branch of the Waipaoa River, North Island, New Zealand.

quickly, forming easier slopes which can be grass-controlled. This causes the upper slopes of the hills to become steeper. More bare rock is exposed and the run-off further increased. The scars we see disfiguring the steeper hillsides are thus seen to be due to the acceleration of the process normally taking place as part of the erosion cycle under forest. The cause of this acceleration is our interference with the plant cover. (Taylor.)[19]

Gullying in Africa

In Africa it is on the gentler, concave lower slopes of the sides of widely open valleys that soil erosion, taking the form of gullying, or "donga" cutting, is most destructive of the land and landscape. "Slope dongas" (Fig. 186), as described by King and Fair,[15] develop as a result of disturbance of the balanced or graded condition of the concave slopes, which they have attained in a landscape cycle culminating in dominance of sheetwash transportation and absence of concentrated rills. Disturbance of natural conditions and stirring of the soil have led first to accelerated sheet erosion.

Secondly, the flow collects into rills which score parallel minor channels, a foot or so deep. . . . Soon these run continuously . . . to the axial stream [of the valley]. Thirdly, the channels are developed into full dongas, partly by deepening and piracy throughout their length, partly by deepening progressing headward from an already incised trunk stream bed. The former arable land is then dissected by a set of parallel slope dongas extending from the base of the boulder-strewn constant slope to the stream flowing along the axis of the valley—an all too familiar sight.[15]

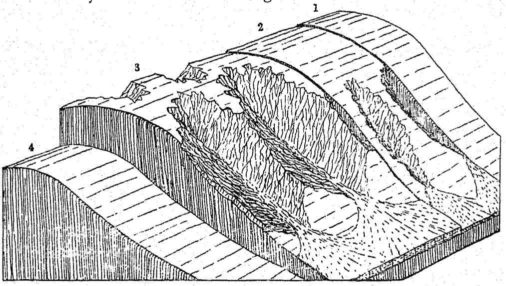


Fig. 192. Successive stages of the cycle of gully erosion on a land surface affected by accelerated erosion. Given sufficient time, the surface will eventually be regraded (stage 4). (From *Geomorphology,* also by the author.)

Accelerated Soil Erosion

Reversion of slopes from a graded to a rough, ungraded state (Fig. 192: 1, 2, 3) is a condition for which apparently there is no cure. In Italy, in China, in the Appalachian province of the United States, and elsewhere, where great quantities of soil have been lost by cultivation of slopes that are too steep, affected slopes have become barren areas of bare rocks or have been sculptured into badland forms. Regrading of such surfaces is an inevitable natural process, but the graded slopes of the future (Fig. 192: 4) will be less steep than those that have been destroyed and the surface must be lowered considerably by erosion before they are developed, and no one can guess how many thousand years will elapse before the process is complete. The critical slope, above which it is dangerous, or impolitic, to clear forest from hillsides, varies widely with the

nature of the underlying rocks and with the climate, and is discovered only by experience. It has been found in most parts of New Zealand that good turf protects slopes very well, though probably not so well as the forest it has replaced; but failure to maintain a continuous cover of grass, where a farm is overstocked or neglected, leads to serious erosion, with irreparable loss of soil and gullying and destruction of the graded surface.

Subcutaneous Erosion

Even though well turfed, some slopes, especially those on loess soils, suffer from *subcutaneous erosion,* so termed by Cumberland[4] (Fig. 193). This is somewhat similar to a deeper subterranean erosion affecting some thick loess deposits in China,[10] in which sinkholes and tunnels develop as a result of corrasion by water that leaks down through crevices. Subcutaneous sheet erosion is followed by

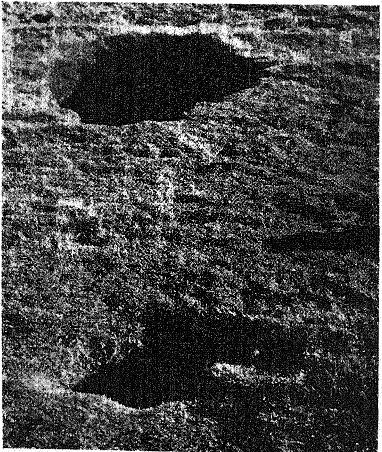


Photo from N.Z. Public Works Department

Fig. 193. Sink holes in a turfed surface over loess or loess-like silt soil, which lead to channels of subcutaneous erosion.

an irregular subsidence of the turfed surface, leading to "subcutaneous dimpling",[4] which leaves a field of hummocks. Channels opened subcutaneously may become unroofed and converted thus into open gullies.

Aggradation Follows Accelerated Erosion

Not only are hill slopes rendered barren where erosion has been accelerated by deforestation, but neighbouring valleys are also injuriously affected. The supply of waste to streams is increased to such an extent that they tend to become overloaded and so begin to aggrade, filling up and reducing the capacity of their channels so that they become subject to frequent floods, and also depositing waste over the valley plains. The first of the soil washed down from eroded headwater slopes may be a welcome addition to that already on the valley plains, but as the process of slope destruction gains momentum this is followed by coarser rock waste, and fertile lowland plains are buried beneath layers of coarse gravel and boulders. The tendency of rivers to flood is increased also as a greater proportion than formerly of the precipitation runs off immediately from the surface, causing greater fluctuation of stream volumes. This is owing to loss from the hill slopes not only of the forest and its absorbent litter but also of the mantle of soil, which has, when present, a great capacity for absorbing rain water and storing it as ground water. From the mature land surface shown in Fig. 191 much soil has been stripped away by accelerated wash, which has culminated in gullying, and the supply of waste to streams is thus greatly augmented. Inspection of valleys, such as that shown in Fig. 194, which become deeply aggraded and choked with coarse debris of such origin in a very few years carries conviction as to the rapidity of soil erosion. Abundant waste rapidly supplied by gullying of slopes has built the talus cone shown in Fig. 195.

Valley-Plain Alluvial Deposits

The actual surface of a flood plain or valley plain developed by lateral corrasion of a river, whether with meandering or braided course, consists of deposited material, but this may be only a veneer of no great thickness covering an abraded rock surface. In the case of the flood plain of a meandering stream the upper layer (consisting of fine silt) grows in thickness during every flood, but in

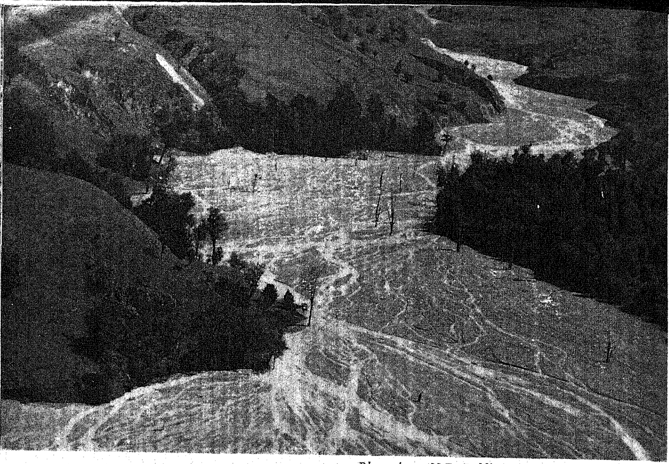


Photo from N.Z. Public Works Department

Fig. 194. Aggradation has buried the flood plain of the western branch of the Waipaoa River, New Zealand. The source of much of the waste deposited here is the "Tarndale slip", the strongly gullied slopes shown in Fig. 191.

streams that are not aggrading this upbuilding of the valley floor is only temporary, for the flood plain is cut away as meanders change their form and sweep down-valley, and silt accumulation must begin again on the gravel flats left by the swinging channel of the stream. The twofold nature of flood-plain alluvium as deposited by meandering streams, where it consists of gravel below with a layer of silt above, as described on p. 171, is regarded as so commonplace by observers in those regions where alluvial deposits are frequently seen in section that it is rarely mentioned even in textbooks.* Challinor[1a] has drawn attention to this and has figured a good example in Wales that shows the gravel underlying silt.

* But see W. M. Davis, *Die erklärende Beschreibung der Landformen*, Leipzig, 1912, p. 54; also Cotton,[3] pp. 111-114; and the first edition of this book, 1941, pp. 124-5, 167. Some textbook statements on the subject are either very vague or actually misleading and show a more or less complete failure on the part of the authors to understand flood-plain development and alluvial accumulation (e.g. R. S. Tarr, *New Physical Geography*, New York, 1909, p. 61; and A. Holmes, *Principles of Physical Geology*, London, 1944, p. 167 and Fig. 77). J. F. N. Green (*Proc. Geol. Assn.*, 58, 1947, p. 128) points out that C. Lyell described the normal succession "inundation mud" over gravel in 1863 in *The Geological Evidence of the Antiquity of Man*.

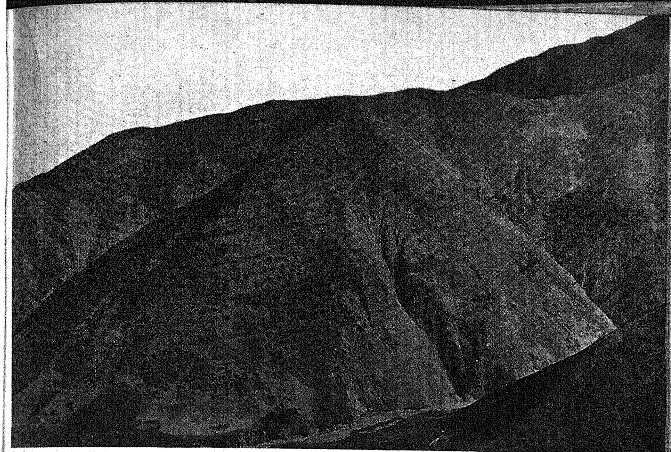
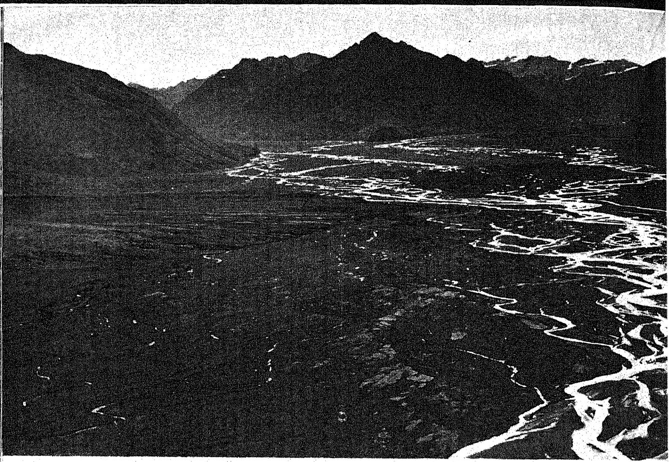


Fig. 195. Soil-erosion gullying and talus cone supplied by accelerated erosion on deforested spurs near Wellington, New Zealand.

The alluvial valley plain of a meandering river is not quite level. In addition to slight across-valley convexity of the whole plain there is stronger convexity as the river channel is approached. During floods the river may be, to some extent, confined to its ordinary channel by *natural levees,* as low, broad ridges of alluvium it builds along its banks are termed.

Aggraded Plains

In contrast with the thin alluvium covering valley plains that have been cut by lateral corrasion, the gravel deposit underlying the valley floor of a river that has aggraded its valley is thicker at least than the depth of the stream channel, and the valley may have been filled to a depth of hundreds or even thousands of feet. The effects are similar whatever the cause of aggradation. The river may be very young and still engaged in filling up so as to build a bridge for itself across a hollow of the initial surface, which may be irregular owing to the occurrence of warping as an accompaniment of the



V. C. Browne, photo

Fig. 196. Aggradation in progress in the glacially eroded (or enlarged) trough of the Rangitata Valley, New Zealand.

initial uplift, or, perhaps, owing to the streams of the present epoch having to grade courses across the irregular slopes and excavated hollows left by the vanished ice of the Glacial Period (Fig. 196). Various causes of temporary aggradation during the course of a normal cycle have already been mentioned in Chapter VI, and deeper aggradation may result from interruption of a cycle by earth movements that involve tilting or warping (Chapter XVIII), may follow in the train of events resulting from general subsidence or rise of ocean level (Chapter XIX), or may be consequent upon a climatic change in the direction of lower rainfall, or upon deforestation and other interference by man with the natural vegetation. Reduced rainfall tends to induce aggradation by increasing the proportion of waste to water in streams, and the effect may be twofold, for not only will there be less water to run off, but almost certainly there will be more waste to be transported as forests die out, or at least become less luxuriant and protect the ground less effectively, under drier conditions (Chapter XIII).

Aggradation in the Glacial Period

During a glacial epoch heavy aggradation takes place in valleys the heads of which are occupied by glaciers and in front of the margins of continental glaciers, especially in a waning phase of glaciation. The abundant waste carried by glacier melt-water, as compared with the smaller loads formerly carried by rivers in the same valleys, has been the cause of the aggradation that has led to the

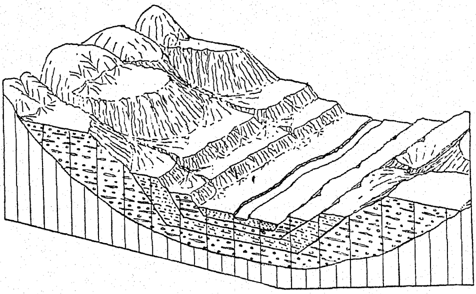


Fig. 197. Successive fluvioglacial valley-fillings forming terraces.

formation of plains termed "valley trains". Later substitution of normal for glacial erosion at valley heads may lead to such restriction of river loads that trenches are cut by the rivers through the valley-train deposits,* and a succession of glacial epochs alternating with interglacial stages of normal erosion may be accompanied by successive aggradational fillings and re-excavations of the non-glaciated reaches of the valleys. A nice adjustment of glacial intensities and a diminuendo of duration of both glacial and interglacial epochs may result in survival of relics of valley trains as terraces, such as are found in the large valleys of the Alps[16] (Fig. 197) and are reported in the Mississippi valley.[13a] The terraces of the Upper Clutha Valley, New Zealand, shown in Fig. 248, are perhaps of this origin, and not cyclic. The surfaces, or treads, of such terraces,

* This sequence is not invariable. Postglacial crumbling of glacially steepened valley walls that have not become forested is still supplying waste in great abundance in the Southern Alps of New Zealand; and under such conditions aggradation down valley may continue.

generally beneath a superficial layer of wind-borne loess, are constructional, gravel-built forms and are thus distinctly different in origin from the cut, valley-plain terraces commonly found developed on both bedrock and alluvium. The higher terraces of a fluvioglacial series are generally somewhat ancient, and so may be expected to be submaturely dissected.

In places where aggradation and degradation due to causes other than glaciation and glacier melting have occurred, terrace remnants of the plains built during aggradational episodes may survive. Inset terraces that border some European rivers are regarded as relics of aggraded plains;[8] but associated with these are probably some that have been developed during a progressive excavation of the already accumulated alluvium while the rivers have been deepening their valleys, as described in Chapter XIII.

Aggrading Rivers

Though it is more obvious that aggradation is in progress where stream courses are braided, meandering rivers may aggrade also. Lateral corrasion accompanying sweeping and the cutting-off and redevelopment of meanders does not in such cases cut the flood-plain deposits entirely away so as to lay bare bedrock in the river channel, but, on the contrary, the building of each new flood-plain strip or scroll starts at a higher level than before, and the meander belt is built up, and so eventually is the whole flood plain. In the lower Mississippi valley, for example, "the flat floor . . . is a surface built as a result of thick alluviation. . . . Meandering is certainly a process to be associated with filling. . . ." (Russell.)[17]

Aggraded valley floors that are built up by streams in braided courses spreading unsorted waste over the whole surface are in humid climates stony and infertile if built of coarse waste, but under semi-arid conditions of weathering and deposition unsorted gravel may contain a sufficiently large proportion of fine unleached rock debris to give it great fertility. Vegetation has little chance, however, of establishing itself on the temporary islands between distributing branches of a braided course.

Should an aggrading river change its habit and cease building up the surface of its plain, entrenching itself perhaps in a new, young valley, such parts of the upbuilt plain as escape dissection have an opportunity to develop a soil covering and become fertile. The

productive Waikato River basin, in New Zealand, owes the formation of its broad valley plains to aggradation which affected rivers flowing from the central volcanic district of the North Island during a phase of copious supply of fragmentary pumiceous volcanic ejectamenta.[13, 18] This specifically light load can be carried by rivers down very gentle gradients, but the abundance of the material led in this case to aggradation, with development of extensive plains of very gentle declivity. That of the Waikato valley has an average fall

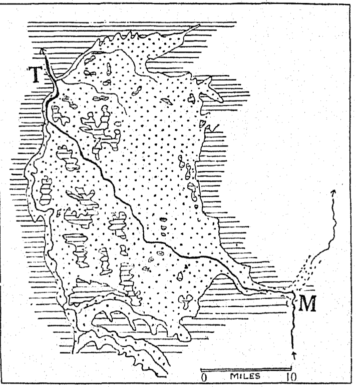


Fig. 198. The aggraded plain of the Middle Waikato, New Zealand.

of 6 feet per mile. It is 500 square miles in extent, spreading out northward and westward over the middle valley basin of the river in fan-like form from an apex at the Maungatautari gorge (*M*, Fig. 198), at which point the river spilled from another course into this lowland during the aggradation. The aggraded basin is surrounded by hills, and the river leaves it by way of the Taupiri gorge (*T*, Fig. 198). The surface of the plain is broken by the emergence of incompletely buried hills, which are parts of a maturely dissected sheet of volcanic material similar to the alluvium of the aggraded plain. The Waikato River, having now a diminished load owing

to a slackening of the volcanic activity at the source of the load material, has cut a trench in its aggraded plain of a depth increasing to 200 feet at the up-valley end.

Ponding by Aggradation

Aggradation in a main river raises the local base-levels to which tributaries must adjust their courses, and so they also are compelled to aggrade their valley floors. If a tributary brings down insufficient waste to allow it to build up as rapidly as its main is doing, its outlet is blocked by the alluvial deposit built by the main across the mouth of its valley, and it spreads out to form a lake. In the lower valley of the Waikato River, New Zealand, aggradation has thus ponded a number of shallow lakes in tributary valleys. The Wairarapa Lake (Fig. 43) is partly of like origin. Lakes so ponded may spill out through new outlets, which become permanent if the rivers entrench themselves in a phase of renewed vertical corrasion. At a late stage of the growth of the aggraded plain of the Middle Waikato basin described above the Waikato's largest tributary, the Waipa, had its course thus permanently changed.[18]

Diversion of Rivers by Alluviation

Main rivers may themselves take entirely new courses by spilling out of valleys they have aggraded through the lowest gaps in their valley walls, being thus "diverted by alluviation" (Gilbert).[11] Generally such a new course will be at first too steep for the diverted river, which must grade a new valley for itself, and as this involves cutting downward, the diverted river becomes fixed in its spill-over course. Diversion in some cases, however, is only temporary. The newly cut outlet trench may be filled up again if the river continues to be well supplied with waste, and, when the new course is built by aggradation higher than the original course, the river will spill back into that again, and thereafter (while aggradation continues) it will occupy and build up the two courses alternately.

A number of clear cases of diversion by alluviation are known among the rivers of New Zealand. The Oreti River, for example, has reached the stage where it has alternative routes to the sea, one directly southward by its present outlet and the other south-

eastward across the Waimea Plain[3] (Fig. 199). The Waikato River also, when it was building the aggraded valley plain of the Middle Waikato basin (Fig. 198), spilled over temporarily eastward from it to an east-coast outlet.[18] Other diversions took place also (at *M*, Fig. 198) during this aggradational phase, one becoming permanent owing to the entrenchment of the river that followed its last spilling back into the present valley from a northward course.[12a, 13]

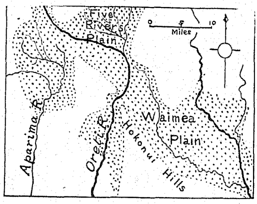
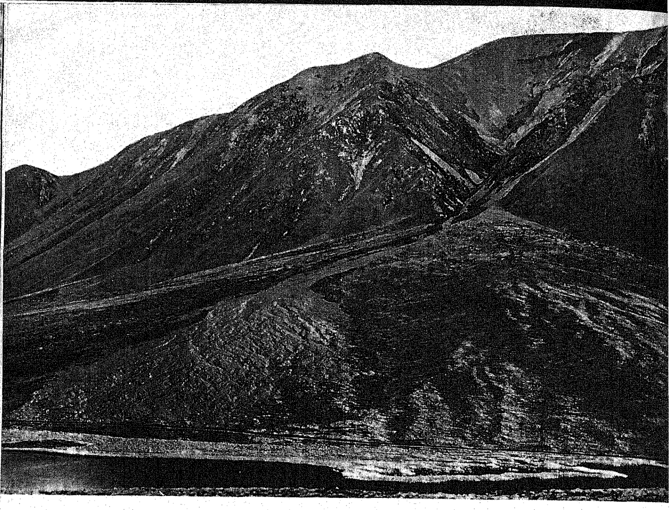


Fig. 199. Alternative courses of the Oreti River, New Zealand, across aggraded plains of its own construction.
(From *Geomorphology*, also by the author.)

Alluvial Fans

As rivers emerge fully loaded from eroded valleys, in which they may be degrading, into broad depressions or basins where slopes are so gentle that the streams are compelled to aggrade in order to prolong their graded profiles—or to build up courses sufficiently steep to give them their needed velocity—they deposit part of their load in such a manner as to build *alluvial fans*, as these forms were named by Drew.[9] They are commonly referred to as "fans", but the recognition of "rock fans" (Chapter XII) may make it necessary to give alluvial fans their full name. The term "fan" was used by J. Haast in New Zealand as early as 1864, but was restricted by him to the subaerial parts of the large confluent deltas and fans that form the Canterbury Plain and are very flat. For the majority of what are now termed alluvial fans in Canterbury he employed the designation "half-cone" because of their greater convexity. "Alluvial cone" (Gilbert[11]) has been used quite commonly as a synonym of "alluvial fan".

The surface of an alluvial fan resembles a portion of a low cone with its apex in the mouth of the valley or gully from which the



V. C. Browne, photo

Fig. 200. Steep alluvial fan, or alluvial cone, fringing a glacially steepened slope beside Lake Lyndon, Canterbury, New Zealand. The postglacial gully above is the source of the gravel in the fan. Average slope about 22°. The lake is impounded and surrounded by this and other fans.

fan-making stream emerges (Figs. 200-202), the slopes being the same from this point down every radius of the fan. The front or toe of the fan is roughly semicircular if built over level ground, but necessarily varies in outline according to any irregularity of the underlying surface, and outlines of confluent fans are modified by interference of each with the free growth of its neighbours. Over a growing fan the stream that builds it flows in the braided channels generally characteristic of aggradation (Fig. 200), and as one set of channels after another is filled up and abandoned the stream flows by turns down every radius of the fan, completion of each set of rays adding a new layer to the fan surface, so that the fan grows symmetrically. Any transverse profile of an alluvial fan, like a section of a cone, is convex, and this convexity, though more strongly marked, is of the same nature as the slight transverse convexity of river plains, for the nearly flat floor of a valley may be regarded as a long narrow fan prevented from extending laterally

by the valley sides. Making use of the term employed by Gilbert, very steep alluvial fans may be distinguished as *alluvial cones* (Fig. 195), and there is a transition through these from alluvial fans to talus slopes (Figs. 189, 200).

Alluvial fans are abundant in mountainous regions where a normal cycle following a period of glacial erosion is still in its youth, for example, in the broad aggraded valleys of the Himalayas[9] (Fig. 201) and of Canterbury, New Zealand, where every small tributary builds a fan (Fig. 202). They are common features also in early

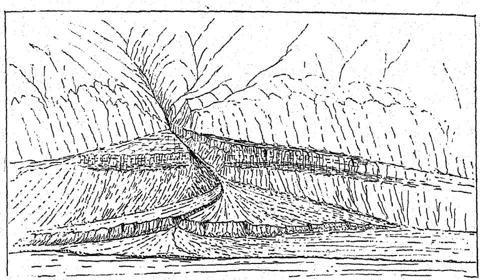


Fig. 201. A three-storied compound fan of alluvial gravels in the Changchenmo Valley, Ladakh. (After Drew, redrawn.)

stages of the geomorphic cycle in regions of strong and diversified initial relief (especially block-faulted range-and-basin regions), i.e. wherever streams flow from dissected higher country into broad depressions, whatever their origin, more especially under conditions of semi-aridity, which result in a high proportion of waste to water in the streams with consequent steepness of aggraded slopes. Under more humid conditions fans, though they may be present, are less conspicuous, commonly because their slopes are gentler.

A fan built by a vigorous tributary may extend across a main valley so as to dam the river in it and form a shallow lake, which overflows in rapids across the toe of the fan. Without actual ponding taking place, the fan of a tributary may force the main river against

V. C. Browne, photo

Fig. 202. Truncated and partly reconstructed ("two-storied") fan, Rakaia Valley, New Zealand.

its valley side, where lateral corrasion perhaps develops an amphitheatre. Where the growth of fans is less vigorous, or the main river more energetic, a swing of the latter to the far side of a broad valley may allow a large fan to be built by a tributary, and when the river swings back the fan may be truncated, cliffed, or almost entirely cut away. Such truncation of the fan, if it shortens the course of the fan-building stream, will compel it to regrade its profile by cutting a trench along that radius of the fan it happens to be flowing on when truncation occurs, becoming fixed in this course for the time being; but another swing of the main stream away from the truncated fan will lead to the growth of a new fan in front of it (Figs. 201, 202), making it a two-storied, or even three-storied, compound fan, and the newer fan may grow to such dimensions as completely to envelop the remnant of the earlier. Fans built in front of the cliffs of a steep coast when the sea has retreated owing to coastal emergence or progradation may be truncated subsequently by wave-cut cliffs. Good examples of fans thus truncated by marine erosion are found in Southern California[7] and on the coast of Wellington, New Zealand.[2, 3]

On rapidly-growing steep fans of coarse waste in humid climates there is little soil and vegetation is generally scanty, for all parts are liable to have fresh layers of clean-washed gravel spread over them. Where, however, the growth of a fan has ceased for a time

owing to the depositing stream's becoming incised and, at least temporarily, fixed in position, soil may be formed by weathering of the surface layer of gravel, to which wind-borne dust may add a quota. In arid and semi-arid regions much fine waste as well as gravel is incorporated in fans as the streams of water dwindle and sink into the ground, and the material of such fans forms fertile soils. Water for irrigation is obtainable from the stream at the apex of the fan, or may be drawn from the ground water in the fan, the supply of which is maintained as the fan-building stream sinks into the porous ground. The ground water may emerge as a line of springs at the toe of the fan; it is nowhere far from the surface, and may be tapped by sinking shallow wells, or by the Persian method of driving tunnels horizontally into the alluvium.

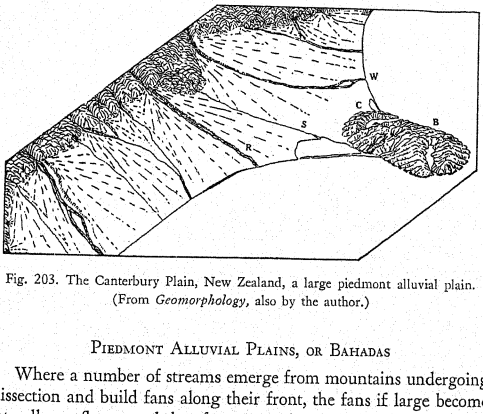


Fig. 203. The Canterbury Plain, New Zealand, a large piedmont alluvial plain. (From *Geomorphology,* also by the author.)

Piedmont Alluvial Plains, or Bahadas

Where a number of streams emerge from mountains undergoing dissection and build fans along their front, the fans if large become laterally confluent, and thus form a continuous apron built of waste bordering the mountains, the surface of which is a *piedmont alluvial plain,* or *bahada* (thus pronounced, and now generally written, but originally the Spanish form *bajada*).[20] It has an appreciable slope away from the mountains, and is made up of a number of convex portions, each of which is one of the component fans (Fig. 203).

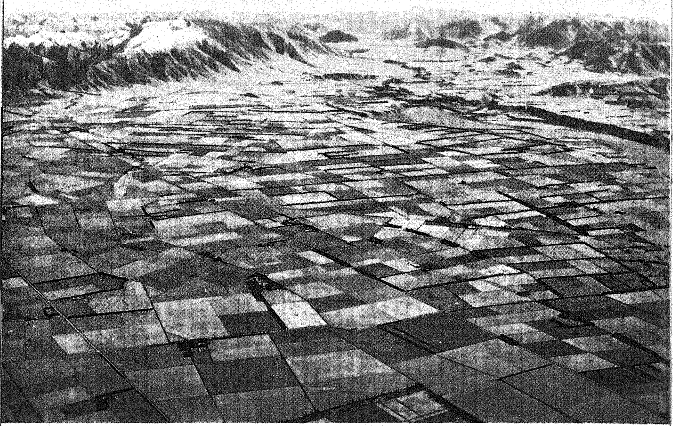


Photo from N.Z. Aerial Mapping Ltd.

Fig. 204. The Canterbury Plain (a piedmont alluvial plain) and the Rakaia Valley, New Zealand. The superposed gorge of the Rakaia River and rock-defended terraces controlled by it are seen at right of centre. The gorge is 600 feet deep.

The directions of the ever-changing courses of streams on a growing bahada are obviously consequent on the slopes of the fans they have built, and they may become fixed in position if, as is the case with the great fan-building rivers of the Canterbury Plain, in New Zealand (Fig. 203), they enter on a phase of vertical corrasion, and cut trenches across the plain (Fig. 204). Smaller rivers either follow consequent courses down the slopes of the fans of their larger neighbours or are *intersequent* (as named by Buwalda)[1] in the re-entering angles of the surface between adjacent large fans—e.g. the course of the Selwyn (*S*) between the fans of the Waimakariri and Rakaia (*W* and *R*) on the Canterbury Plain (Fig. 203).

Basin Plains

Basin plains, which are closely related in origin, structure, and form to bahadas, are widespreading alluvial plains made up of confluent fans built by streams entering from various directions

intermont basins of tectonic origin—i.e. resulting from warping or faulting of the land surface on a large scale, or from some combination of the two. Though plains, they are far from plane, if composed of contiguous gravel-built fans of steep-grade streams (Fig. 205, rear), but large basin plains that are built in part of broad fans of finer waste are more nearly level in their central or axial portions. The Vale of Kashmir is an example of a large-scale basin plain with an area of about 5000 square miles; like most others it has suffered a certain amount of dissection as the outlet gorge of the Jhelum River has been deepened.

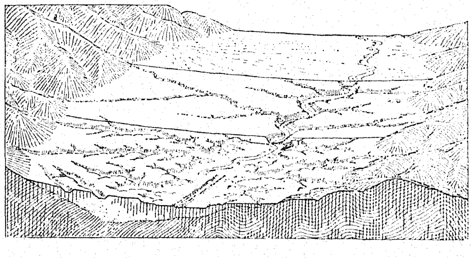


Fig. 205. Three stages in the history of a basin plain, the Valdarno, in Italy. (After Davis.)[6]

Commonly the alluvial deposits built into basin plains have been more or less eroded, and throughgoing rivers easily cut them down to valley plains of lateral planation, bordered for a time by terraces which are remnants of the aggradational surface (Fig. 205), or, more commonly, by flights of terraces cut in the alluvial material. The Mackenzie Plains of New Zealand, however, retain the aggradational basin-plain surface only slightly modified (Fig. 206), and the plain in the Culverden basin (Fig. 123), fully 100 square miles in extent, is a depositional surface still patterned over with braided stream courses (compare Fig. 175). Dissection to youth and to submaturity of a basin plain is illustrated in Fig. 205, taken from a description by Davis[6] of the Valdarno, a basin plain in an intermont basin of the Apennines.

V. C. Browne, photo

Fig. 206. A basin plain, the Mackenzie Plains, South Canterbury, New Zealand.

Texture and Structure of Alluvium

Deposits of gravel in fans and bahadas and underlying aggraded plains exhibit a rough stratification parallel to the surface. Each layer has been built up, however, by the filling of a great number of separate channels successively occupied, and so, where seen in section, the beds are lenticular, thickening and thinning irregularly and passing laterally by rapid transition into coarser or finer material (lens-and-pocket stratification). There is nothing here comparable to the complete sorting of material that takes place during deposition in the sea or a lake, where waste of different grades of fineness is deposited in different places, so that the material in a particular portion of any stratum is of even size; but there is generally a certain amount of rough sorting, and some lenses of sand or sandy clay may accumulate in abandoned channels that have become backwaters, to be covered later by gravel lenses. Coarser and finer gravel lenses may be present also, but there is generally much mixture of coarse and fine gravel with some finer material throughout. In fans built by vigorous mountain streams large boulders may be present scattered through the gravels, indicating that mass move-

ments of the nature of mudflows have taken part in distributing the debris. Under humid climate conditions the gravel is cleaner-washed and more thoroughly freed of admixture of fine material than in the case of the unsorted waste built into the fans and bahadas of arid and semi-arid regions.

Great piedmont plains of finer waste and of gentler slopes than these gravel-built bahadas have been spread out by rivers in various parts of the world. Two of the best-known examples, the plains of northern India and those bordering the Rocky Mountains on the east, are somewhat dissected, but the vast south-eastern plain of Turkestan is still in course of aggradation. Here

> every grain of sand and silt that the Tejen and Murg-ab bring from the mountains of their upper courses must be deposited on the plains, where their lower courses wither away. The plains are dead-level to the eye; yet the muddy rivers detect a slope. . . . The habit that these rivers have of flowing on the plains, instead of in valleys eroded somewhat below the plains, is highly suggestive. Such a habit is easily explained as a necessary consequence of the formation of the plains by rivers; it would be difficult to explain it if the plains had been laid down in a sea or lake basin and then laid bare by uplift. (Davis.)[5]

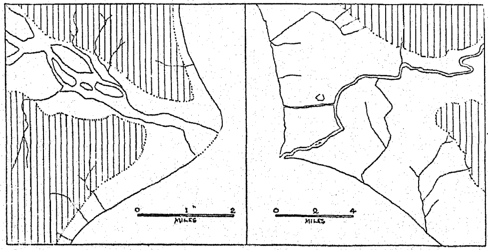
Deltas

Where waste is deposited at the mouth of a river in a body of standing water, either the ocean or a lake, the shoreline may be built forward, some new land being formed. Where such natural reclamation takes place, the new land formed is the emergent part of a *delta,* a name used in the fifth century B.C. by Herodotus for the delta plain of the Nile.

A delta is built only when the river supplies more waste than can be carried away by tidal or other currents assisted by wave action. Thus deltas are commoner in lakes than bordering the ocean, for in lakes there are no appreciable tides, and currents and wave action are generally weaker than in the ocean. Deltas are common at the heads of, or quite filling, estuaries, into which rivers have discharged as a result of a late partial submergence of the land margin. Such *bay-head deltas* (Fig. 207) do not exhibit the triangular outline of the Greek capital letter from which they are named; but vigorous rivers fill their estuaries with deposited material and

V. C. Browne, photo

Fig. 207. A lake-head delta, which resembles a bay-head delta, Lake Alabaster, Fiordland, New Zealand.



A *B*

Fig. 208. Typical salient deltas; *A*, delta of the Clarence River, N.Z.; *B*, delta of the Tiber. (Compare Fig. 208A.)

V. C. Browne, photo

Fig. 208A. Salient delta of the Clarence River, New Zealand.

then build out coastal salients of the true "delta" form, which is assumed also by the deltas of rivers that afford no evidence of having filled up coastal embayments (Fig. 208). Further outgrowth of fingers or pairs of natural levees at the mouths of distributaries makes the digitate, or "bird-foot", form assumed by the great delta

Fig. 209. The bird-foot delta of the Tongariro (Upper Waikato) River in Lake Taupo, New Zealand. *V. C. Browne, photo*

V. C. Browne, photo

Fig. 210. Confluent deltas of small streams from the Seaward Kaikoura Range build the Kaikoura piedmont plain, New Zealand.

of the Mississippi and occasionally imitated by small deltas in lakes (Fig. 209).

Deltas of closely spaced streams, if they become confluent, build piedmont plains like that of Canterbury (described above) and a smaller example which also fringes part of the east coast of the South Island of New Zealand and lies at the base of the Seaward Kaikoura Range (Fig. 210).

The small deltas built by steep-grade streams carrying gravel into lakes serve as a type of all deltas. These deltas and their structure have been described by Gilbert.[12] Not only are the subaerially formed surfaces of such deltas visible, but also, very frequently, the parts laid down under water have also emerged as

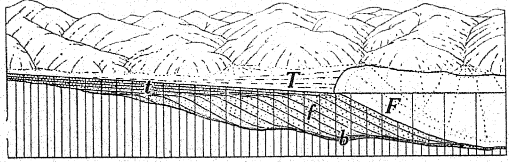


Fig. 211. The structure of a delta of coarse material at the head of a lake or bay. (From *Geomorphology*, also by the author.)

landforms owing to lowering of the level of the lake. The internal structure, which is of great interest because of its relation to the form of the surface, may often be seen moreover (as in Fig. 211) where the stream that has built a delta has afterwards cut a trench in it as a result of the lowering of the level of the lake. The upper or subaerial surface of one of these small deltas resembles an alluvial fan, having been formed in an exactly similar way by an aggrading stream flowing in shifting channels and forced to add layer after layer to the upper surface, in this case in order to maintain a slope sufficiently steep to keep it flowing and transporting its load as the size of the delta increased, prolonging the stream course. Aggradation extends, indeed, far upstream, forming an aggraded valley plain that is an inland extension of the delta (Figs. 152, 207). The aggraded slope is the *top-set* slope of the delta (Fig. 211, *T*), taking its name from the materials of which it is built, the top-set beds (*t*). The subaerial top-set slope is continued with little change as a subaqueous top-set slope below lake-level for a short distance, until it descends to the limiting depth to which wave action stirs the lake waters. Here it gives place rather suddenly to a very much steeper slope, the *fore-set* slope (*F*), that forms the front of the delta. The bulk of the gravel forming the delta and underlying the top-set beds is stratified as fore-set beds (*f*) parallel with this slope. These entirely subaqueous beds may dip at an angle as steep as 30°, and the surface of each marks a former position of the fore-set slope of the delta, which was continuously built forward as gravel was poured over its edge and came to rest in the still, deep water at the angle of repose. Fore-set growth may extend the delta margin in lobes at the mouths of distributing streams, thus giving the delta a "lobate" form.

The mud that is brought into the lake does not accumulate with the gravel in the fore-set beds, but remains long enough in suspension to be carried by lake currents to a considerable distance. It eventually sinks and forms a layer of silt all over the bottom of the lake, smoothing out its irregularities to some extent, and lying more or less horizontally. Thus lake-floor plains are deposited, and some of them are exposed as dead-level subaerial plains of great fertility, where lake waters have been drained off. Some of the silt layers are incorporated in the growing delta as fore-set beds are built over them, and thus become its *bottom-set* beds (Fig. 211, *b*).

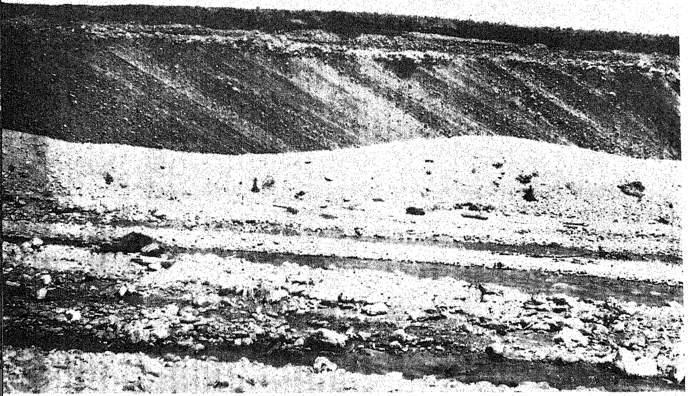


Fig. 212. Fore-set and top-set bedding in a dissected delta, Lake Wakatipu, New Zealand.

The deltas built by large rivers of low gradient, which carry finer waste, are similar in a general way to the gravel deltas that have been described, with the important exception that their top-set and fore-set slopes are very much less steep, the former being almost perfectly horizontal and very liable to flooding. Near the margin accumulation of sediment may take place in lagoons enclosed by sand bars thrown up by waves along the seashore, as occurs conspicuously in the case of the Nile delta. Swamps are thus formed, but, as a delta continues to grow, these areas, the filling of which is a phase of top-set deposition, may have their level raised by the addition of layers of ordinary top-set alluvium.

In the case of the Mississippi, which builds the extreme type of bird-foot delta, alluvial deposition prevails over wave action, with its attendant beach and sand-bar construction, so that the mouths of distributaries of the aggrading stream are extended into the shallow marginal sea between seaward extensions of their natural levees. The marginal zone of shallow water has beneath it the very gently inclined subaqueous extension of the top-set slope. In all

deltas built into the ocean or large lakes this continues seaward into water of considerable depth (to the level of "wave-base", below which the water is not stirred by wave action), and gives place somewhat suddenly, at a fairly definite line, to the steeper fore-set slope (with a maximum inclination of about 5°) of the delta front, on which, settling from suspension, sediment remains at rest.

It seems that fore-set *beds* have very little part in the building of very large deltas, and their absence can be accounted for as a result of the subsidence that accompanies the accumulation of the very thick top-set sediments of which these deltas are composed.[17] As regards surface form, however, the contrast between top-set slope (strictly absence of slope) and fore-set slope is very striking.

Collateral evidence of progressive down-warping of deltas is found at their lateral margins, where large shallow lakes are common.[17]

Delta Plains

The subaerial parts of the top-set portions of the deltas of the great rivers that carry fine waste are *delta plains* of rich land. The great plain of the Huangho delta, with an area of 100,000 square miles, and supporting a vast population, is an example. The river frequently changes its course, and there are historical records of many disastrous floods, as well as of major diversions of the main stream resulting from its own aggradation. It has found its way to the sea sometimes north and sometimes south of the Shantung Peninsula, formerly an island but joined to the mainland by growth of the delta (Fig. 213).

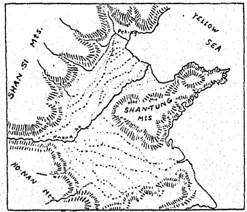


Fig. 213. The Huangho delta, showing former courses of the river. (After Blackwelder.)

Another illustration of the instability of river courses on deltas is afforded by the delta of the Colorado, at the head of the Gulf of California. The delta extends right across a deep fault-bounded depression, so as to divide it into two parts, the Imperial Valley to the north and the Gulf of California to the south. The former had been a lake whenever the Colorado had flowed into it, but when man came on the scene the Colorado was flowing directly to the Gulf and the lake had been dried out by evaporation leaving an extensive lake-floor plain of fertile soil, 2200 square miles of the basin floor being below sea-level. Left to itself the Colorado River would one day have again taken a more northerly course and refilled the lake basin with water. Man, however, hastened the process by attempting to lead a stream of water from the Colorado into the Imperial Valley to irrigate its fertile soil. The river enlarged the irrigation canal, abandoned its former course for this new one, and poured a vast stream into the valley until again diverted by a feat of engineering, though not until it had succeeded in re-creating the "Salton Sea" with an area of 410 square miles, since reduced again to small dimensions by evaporation.

The city of Christchurch, New Zealand, is somewhat insecurely situated on the delta of the Waimakariri (Fig. 203, *C*), and in its vicinity are some recently abandoned beds of that river—wastes of bare gravel, with braided channels and occasional sand dunes—which indicate that the river has had its outlet sometimes north and sometimes south of Banks Peninsula (Fig. 203, *B*).

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CHAPTER XVI

Peneplains

PRESENT-DAY LANDSCAPES BELONG, AS A RULE, TO ONE OF THE EARLIER stages of the geomorphic cycle. There have been so many earth movements and changes of ocean level in recent times that the current cycle has scarcely anywhere advanced beyond the stage of full maturity, except locally on very weak rocks; but, though young and mature forms are now predominant, forms developed in late-mature and senile stages of earlier cycles have not been entirely obliterated. Some have been uplifted, with the result that they have become the initial surfaces on which erosion has begun to cut landscape forms of newer cycles. Others have been submerged at various periods during the long past history of the earth, and preserved beneath sedimentary deposits. From evidence afforded by relics of imperfectly dissected uplifted surfaces and by resurrected parts of buried landscapes of the past it is known that many extensive surfaces of very small relief truncating diversely folded and dislocated rock structures were developed by erosion in bygone periods; and it is for the explanation of the origin of landscapes of former cycles, rather than for the description of the rare examples in which the slow processes of post-mature erosion may still be operating, that the deduced scheme of the features of senility of the cycle has its chief importance. The deduction must be made with extreme care, for this hypothesis of destruction of relief is only one of a group of hypotheses that have to be considered as possible explanations of the formation of the plains and plateaux of past ages. Other hypotheses are, for example, that of lateral planation (Chapter XII), that of development as desert pediments, and that of marine erosion.

OLD AGE IN THE CYCLE: THE SENILE LANDSCAPE

The inevitable result of the uninterrupted action of the normal processes of landscape erosion, working under unchanging climatic conditions, widening the already flat floors of river valleys and lowering the land surfaces between them, is the reduction of the whole, or in a penultimate stage almost the whole, of a region to very faint relief. In the stages of late maturity and old age graded valley floors will be cut down to levels somewhat lower than those

of early maturity owing to the reduction in the supply of waste to rivers when the heights and slopes of the interfluves have been lowered. Such lowering takes place so slowly, however, that widening out of valley floors must go on continuously with it, the general result being a flattening down of, or destruction of relief over, the whole surface. The surface of small relief that results in the senile, or old-age, stage of the cycle—not quite a plain, but nowhere far from level—is a *peneplain*. The term "peneplain" was invented by Davis in 1889[10] to define this concept. Johnson[26] has preferred to use the spelling "peneplane", and has proposed to widen the concept to include all surfaces levelled by erosion; but this usage has not many followers. Davis has translated "peneplain" into German as *Fastebene,* a word rejected by W. Penck[36] in favour of *Endrumpffläche* or *Endrumpf,* which implies an "end" form. Such an ultimate erosion plain (or plane) can be only an abstraction, as the time required for its development, at any rate by the processes of normal erosion, is infinite. Davis's conception of the peneplain is not, however, such a hypothetical end form, but rather the attainable or penultimate product of the erosion cycle.

As old age comes on, the mounts and hills, already well subdivided and subdued, are reduced in area and worn down to so moderate a relief that no sharp line of demarcation can be drawn between their slopes and the margin of the ever-widening and slowly lowering valley floors; but a zone of transition may be recognised where the convex profiles of the residual hills gradually become concave as they are continued down to the broad valley floors, which slant very faintly toward their streams. By this time the rainfall, increased at the time of original upheaval, has lessened in consequence of loss of mountain altitude; and the discharge of rainfall in rills is also decreasing, not alone because of diminishing supply but also because a greater share of the rain that falls soaks into the ground, now that the slopes are weaker and the soils are deeper. Hence the direct run-off is decreased and a larger proportion of the rainfall is delivered to the streams as ground water emerging in channel-side springs. The brooks and rivulets may, therefore, lose some of the headwater length that they enjoyed earlier, when slopes were steeper; and with this loss the widely opened ravine heads may be somewhat obscured by soil creep. (DAVIS).[18]

Slopes are now so gentle that there is no longer any possibility of headward erosion, such as might lead to the development of

L. C. King, photo

Fig. 213A. Low undulating relief of a land surface approaching old age, Maritzburg peneplain, Natal, South Africa. Such a landscape has been called a "matureland" by Willis[47]; but others prefer the description "postmature". It is senescent rather than senile.

new subsequent valleys. The process of adjustment to structure has, indeed, long ago slowed down and ceased, and some of the adjustment attained in the stage of early maturity may even have been later lost at places where lateral planation, extending valley plains, has cut through the now deeply weathered outcrops of resistant rock strata that were formerly the sites of strike ridges.

Near the sea the land surface will now be nowhere far above the general base-level, but,

> if a peneplain, thus worn down, extends a thousand miles from its ocean border into a continental interior, its old rivers with a fall of one or two feet to a mile will not reduce its interior parts below an altitude of 1000 or 2000 feet; hence, while a peneplain is a surface of low relief, it is not necessarily a lowland over all its extent.[18]

Unlike a valley plain, which is a true plain cut by lateral river corrasion, a peneplain is not an almost perfectly flat surface throughout. It does indeed consist in part of the wide valley plains bordering the larger rivers and the narrower flood plains of smaller streams, but between these are extensive areas of low undulating relief (Fig. 213A) with very gentle graded slopes and no rock outcrops. In 1914 the late Professor Davis for the author's benefit defined the limiting steepness of the slopes of a peneplain as such as one might lay out a straight road on in any direction "and trot on it". In these days this would be a high-gear road.

> A small difference of altitude must long remain between broad hill arches and broad valley floors, even though it is a diminishing

difference. The main divides between the larger, opposing rivers of the region will be reduced to low and broadly convex swells, delicately diversified by wide-open and shallow valley heads of branching streams. Minor divides will be of similar but less pronounced form.[18]

The conception of peneplanation by gradual expansion (simultaneously with the gradual reduction of surviving salient forms) of systems of branching nearly flat valley floors, so that these become eventually a major feature of the senile landscape, distinguishes the peneplanation process from that of development of plains by lateral planation, however effective the latter may possibly be in levelling extensive plains in zones bordering mature mountains (Chapter XII). Should such a zone of lateral planation have been developed in late maturity of the cycle of erosion, it must persist as a fringe around the peneplain that later takes the place of the mature mountains. Thus peneplains and plains of lateral planation are closely related, and may be very closely associated.

Monadnocks

Above the general level of a peneplain a few isolated groups of hills, even subdued mountains, generally remain standing (Fig. 214), and to these the name monadnocks is applied, "taking the name from a typical residual mountain which surmounts the uplifted peneplain of New England in south-western New Hampshire"[12] (Fig. 215). Monadnocks are remnants of dividing ridges, or of the mountain knots where several divides meet, and are generally composed of the resistant rocks of the region, for on the outcrops of these the divides have become fixed in an earlier stage of the cycle of erosion. Thus it is unpromising of result to attempt to distinguish monadnocks due to superior hardness from others accidentally situated.*

Peneplanation a Slow Process

The time required for the change from mature to senile relief must be many times greater than that which elapses during dissection to the stage of maturity, for the rate of erosion on slopes becomes exceedingly slow as the slopes become gentle. So slow does the mechanical removal of waste from the gentle slopes of a senile surface become that chemical erosion, relatively unimportant on most rocks in the earlier stages of the cycle, when mechanical

* *Härtlinge,* of Spethmann, and *Mosore,* of A. Penck, respectively. (See Davis.)[15a]

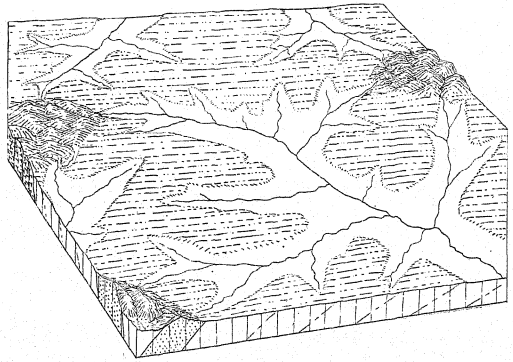
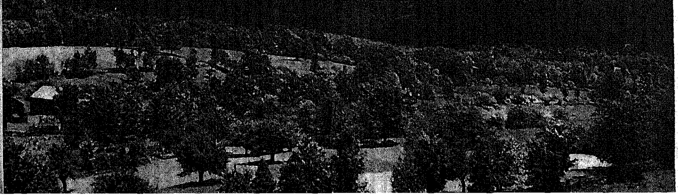


Fig. 214. A peneplain with monadnocks.
(From *Geomorphology*, also by the author.)

erosion was more active, is now responsible for a great part of the lowering of the surface, as the soluble products of rock decay are removed in solution. According to Powell,[38]

the degradation of the last few inches of a broad area of land above the level of the sea would require a longer time than all the

Fig. 215. A typical monadnock, Mt Monadnock, New Hampshire. *C. Keene, photo*



thousands of feet which might have been above it, so far as this degradation depends on mechanical processes; . . . but here the disintegration by solution and the transportation of the material by the agency of fluidity come in to assist the slow processes of the mechanical degradation, and finally perform the chief part of the task.

"Chemical weathering is believed to play the largest part in maturing the almost stationary soil cover, even to the point of decomposing feldspars, extracting their silica, and leaving the residue as hydrated alumina or bauxite" (DAVIS).[18] For the development of a peneplain across resistant rocks, therefore, an enormous period must be required, perhaps many millions of years, but, on the other hand, so great are the differences in rates of erosion on different rocks that a district of very weak rocks may be reduced to a peneplain in a very small fraction of the time required to produce a similar result even on rocks of average resistance, or on a mixed assemblage of weak and resistant rocks. So slow must be the process of peneplanation on resistant rocks that the probability of the occurrence of a sufficiently long still-stand, or period of immunity from earth movements, for the full development of extensive peneplains is sometimes questioned, and the German geographer Passarge has denied the possibility of sufficiently long continuance of uniformity of climatic conditions for the completion of a cycle.

In the present unstable condition of the earth's crust and of sea-level, when landscape evidence of either recent movement or dis placement of base-level is very nearly ubiquitous, examples are rare of peneplains in an undisturbed and undissected condition. Even landscapes with wide valley floors of late maturity, such as have been described as transitional to a senile surface, or peneplain, are of rare occurrence in a condition where they are still progressing towards senility in an uninterrupted cycle. It is very exceptional, that is to say, to find them traversed by rivers at levels which, as local base-levels, still control the uninterrupted development of a peneplain. The existence of an actual undisturbed peneplain still undergoing uninterrupted development as such has been recorded, however, by Davis[13] near Semipalatinsk, in Siberia. Traversed by the Irtysh River it is "a great steppe of small relief, a worn-down surface of crystalline and greatly deformed stratified rocks; by far the best undissected peneplain I have ever seen" (DAVIS).

SLOPE RETREAT, OR BACK-WEARING, AS A PROCESS OF PENEPLANATION

In the account of peneplanation given in the preceding paragraphs this has been interpreted mainly in accordance with the "down-wearing" theory of Powell and Davis modified, as Davis[18] himself modified it, by the introduction of the concept of progressive lateral enlargement of valley floors at the expense of the area of residual hilly interfluves. It is implied that a region eventually reduced to a peneplain has been first maturely dissected throughout.

There are many cases known, however, of survival of considerable areas of what are believed to be ancient peneplains flanked by lower-level and generally younger peneplains in a manner which will be referred to again in Chapter XIX. The descent from the higher to the lower peneplain in such a case may be made in a fairly broad zone of maturely dissected landscape, or, again, the transition zone may be narrow—so narrow, it is claimed, in some cases that it may be termed a scarp. This scarp, or almost scarp-like slope, is obviously migrating, with the result that the lower-level peneplain is gaining in area at the expense of the remnant that survives of the landscape at a higher level.

Consideration of such cases has led to advocacy of a theory of "back-wearing" of the scarp as the principal cause of the development and extension of the lower peneplain, a concept which some regard as having features in common with Walther Penck's explanation of the widening of lowlands and consumption of upland residuals (Chapter XIV). In the case of the Northern Drakensberg scarp, for example, which descends to the lower level of Natal from the interior African plateau of the High Veld, peneplanation at the lower (Natal) level is developing at the expense of the higher inland plateau. The scarp separating them, which is part of the African "Great Escarpment", is obviously migrating.[30] Another example is a scarp in South Dakota which separates the White River lowland from the higher Missouri Plateau surface. "It fully merits the local name 'wall' which has been given to it. . . . The significant fact is that the wall is a retreating erosional escarpment moving steadily away from the White River."[33] Meyerhoff[33, 34] maintains the opinion that the process of back-wearing, or scarp retreat, is in the main responsible not only for the development of new but for the destruction of higher (which are generally older) peneplains. It is recognised that upland plateaux that preserve in a

general way the forms of ancient peneplains are not actually those ancient surfaces, for they have been subjected to wear by weak erosional processes operating slowly throughout vast periods; but it is claimed that, notwithstanding this small amount of down-wearing, such a plateau is scarcely changed at all in form. It remains "a gently graded surface, in equilibrium . . . , and this equilibrium is maintained over the entire surface."[33]

There are at least two ways in which the scarp at the boundary between such a high-level peneplain and the erosion surface developing in the direction of peneplanation with respect to a lower base-level may encroach upon and eventually destroy the higher surface. One is by gullying and progressive dissection such as is effected by headward-eroding streams; another is by retreat of a wall-like scarp along which gully heads and out-jutting spurs are only minor irregularities. Back-wearing of the latter kind is well established in arid and semi-arid regions, and under more humid ("normal") conditions of erosion Meyerhoff,[33] Bryan,[6] King,[30] and others have pictured a generally similar retreat in operation, though full agreement has not been reached as to the mode of operation of the processes involved. Gullying, rain-wash, and mass movement of waste take part. In the general case, not controlled by rock structure, Meyerhoff pictures a sapping operation going on at the rear of a gentle basal "wash slope", which undermines and causes retreat of a steeper "gravity slope" above. There is some support for the opinion that such slopes as they retreat maintain their steepness unchanged. (The "wash slope" may be compared with Penck's *Haldenhang* and the "gravity slope" with his *Steilwand*.)[36] Bryan[6] remarks: "If this question of flattening [i.e. reduction of steepness] be considered *a priori*, what reason is there for assuming a continuous flattening?" The question is still a controversial one, however, and the thesis of down-wearing has been maintained by Rich,[41] who states: "After the drainage system has reached grade the dominant activity is a gradual flattening of slopes and general lowering of the interstream areas by sheetwash and creep."

Old-from-birth Peneplains

The inevitability of the destruction of all prominent relief forms by long-continued erosion is accepted alike by those who agree that normally landscapes pass through the cycle stages of youth and maturity, leading on to old age, and by those who do not. Some

of the latter stress the possibility of very slow uplift continuing for a vast period, throughout which erosion proceeds. Valleys are deepened about as fast as the land is raised, but the rate of uplift is assumed to be so slow that valleys are widened more rapidly than they can be deepened, with the result that interfluves of the pre-existing surface (possibly flat) are worn down almost as fast as they are raised, and no sharp forms are ever developed, however long uplift continues. A surface so degraded will be always practically a peneplain during the continuance of a vastly prolonged uplift, which must be accompanied in the case of an upheaval of some magnitude by an enormous amount of erosion.

Such, possibly, may be the history of some locally developed peneplains and plains of lateral planation confined to the limits of very soft rock formations; but it is a highly improbable explanation of extensive peneplains truncating resistant rocks. This conclusion cannot be avoided when the extreme slowness of erosion and transportation of waste down the weak slopes of a peneplain, and the extreme slowness, therefore, of the rate at which such a surface can be worn down, are taken into account. Slowness of erosion is confirmed, if such confirmation be necessary, by the great thickness of weathered waste which overlies the bedrock of a peneplain, and by the advanced stage of chemical weathering to a bauxitic or lateritic residue often found. An eternity would, apparently, be required for the removal by erosion under these conditions of the vast thickness of rocks which, it cannot be doubted, have been cut away from above peneplains that truncate folded and other formerly deep-seated rock formations, especially some metamorphic rocks the presence of which at the present-day surface must indicate that a rock layer at least ten miles thick has been eroded from it. The arguments showing that this theory makes an extravagant demand on time are so obvious that it is hard to imagine the reasoning behind an opinion expressed by one geomorphologist (quoted by Davis[19]) that this mode of peneplanation is, on the other hand, economical of time as compared with the rival theory of transition of the surface to old age through young and mature stages, during which it cannot be doubted that lowering of the surface has proceeded at an incomparably rapid rate.

Where slow uplift of a district of extremely weak rocks does lead to wasting away of the surface during uplift without development of any forms of strong relief, the conditions may be considered

to constitute a special case of the cycle of erosion in which the stages of youth and maturity are both elided. A landscape with such a history is described as "old from birth".[16] Almost the only suggestion that has been made of a means of distinguishing an "old-from-birth" peneplain from one that has passed through a condition of mature dissection is that the former may be expected to exhibit less complete adjustment to structure than the latter.

In some of his later writings devoted to the rehabilitation of the cycle theory after it had been adversely criticised and discarded by one of its former supporters (Albrecht Penck), Davis[16] drew attention to the way in which the case of old-from-birth peneplains and various other special cases could be fitted in with the general theory. Some criticisms of the applicability of the cycle scheme as the basis of a system of nomenclature of landscape types have been offered on the ground that replicas of so-called young, mature, and old landscape forms may make their appearance in an order different from that required by the general theory and suggested by these names, being perhaps developed even in reverse order. Such criticisms are met by taking into account those special cases, or variants, of the ideal cycle in which slowness of uplift or weakness of the rock materials undergoing dissection makes erosion during uplift important because relatively rapid, and by taking into consideration also the effects of changes in the rate of uplift during a long erosional history. Examples are known (the Central Plateau of France is cited by Davis) of uplifted peneplains in a cycle of renewed erosion on which headwater streams flow in shallow, open valleys, apparently mature-born in the new cycle, though larger rivers have cut narrow, deep, young valleys; that is to say, old forms (of an earlier cycle) seem to have been replaced by mature-born forms, and these in turn are being replaced by young forms.

The following is a selected special case of varying rate of uplift imagined and deduced by Davis, and described in terms of the cycle stages:

> One may conceive of a region that, after a first very slow uplift, is uplifted more rapidly, but eventually stands still for an indefinite period; and in such a case the expression of the first-developed valleys would be "old"; then, as the rate of uplift increased, the "old" valleys would be first incised by "mature", and then by "young" valleys; and finally the "young" valleys would, during the

ensuing still-stand period, gradually gain the appearance of "mature" and "old" valleys.[16]

Even in such a case the first-developed, or "infantile", valleys should be distinguishable, at least theoretically, from old valleys, as their gentle lower side-slopes may be expected to be convex instead of concave. "These so-called old and mature forms of early development are merely peculiar kinds of young forms."[19]

The theoretical distinction between infantile forms developing on a peneplain as it is slowly uplifted and the senile forms it exhibited before uplift was first made by Walther Penck.[36] Davis[19] agreed with him in attributing convex valley-side slopes to infantile as well as to later more deeply cut valleys developed during accelerated uplift. Penck has termed an undisturbed peneplain an *Endrumpf,** but distinguishes from this a surface that has begun to feel the effects of slow uplift as a *Primärrumpf.*† It is a surface which, according to Davis's terminology, will exhibit infantile profiles. An old-from-birth land surface, provided that a sempiternally slow upheaval to which it owes its form is still in progress, must be exactly like this and so is also described by Penck as a *Primärrumpf.*

According to von Engeln,[20] "when *Endrumpf* is used, a German writer means that he considers the surface in question to be the end stage of a land mass that originally had high relief but has been levelled down by degradation". When, on the other hand, "a portion of the sea floor is lifted above sea-level," old-from-birth development produces a *Primärrumpf* on it, and "such would be the initial circumstances of all new land masses". This application to first-cycle development is inconsistent with the implication in the use of the *Rumpf* compound of "the existence of a torso, or massive body of rock" (VON ENGELN), and for the amelioration of this inconsistency a German textbook-writer (Machatschek) has introduced a naïve new term *Trugrumpf* (pseudo-torso) for any such "torso" that is not a true torso.

In Penck's scheme of accelerated uplift, introducing renewal of vertical corrasion as a preliminary to mountain sculpture, the

* *Rumpf* in this compound word is a contraction of *Rumpffläche,* which may be freely rendered as "planed-down torso" or "planed-down massif".

† Davis did not in his discussion of this concept, in which he described the valley forms on a *Primärrumpf* as infantile,[19] suggest an English equivalent for the German term; but it is rendered as "primary peneplain" by Sauer.[42]

Primärrumpf is merely an abstraction, for continued erosion has destroyed it. Davis[19] has, however, compared the ideal profiles of the *Primärrumpf* and *Endrumpf* (or peneplain) copied from Priem, who obviously had enormously exaggerated the vertical scale (Fig. 216). The peneplain profile, it will be noted, assumes a surface without any rounded convexities but with angular ridges separating broad concave valleys. This is a deduction from Penck's theory of horizontal valley-side retreat in a phase of waning development* (Fig. 187), and is incompatible with the more widely accepted idea of dominance of broadly convex forms and ill-defined divides on the interfluvial parts of peneplains. According to Baulig,[3] "the

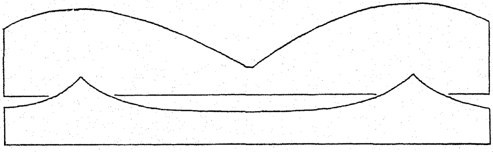


Fig. 216. Priem's profiles of a *Primärrumpf* (above) and a peneplain (below). (After Davis.)

Primärrumpf, the initial term of an ascending [waxing] series, and the *Endrumpf,* the final term of a descending [waning] series, are indiscernible not only in nature but even in theory".

"Observable forms", Baulig tells us, "express equilibrium, but are silent as to how equilibrium was reached." He continues:

This being true, the problem set by Penck, viz. from present forms of valley-sides to deduce the past rate of river-bed erosion, and hence that of land-mass uplift, is wholly undeterminable. It admits of any number of solutions, all equally plausible, all equally undemonstrable. It must remain undemonstrable even if the numberless possibilities of nature are arbitrarily reduced to Penck's single alternative: either ascending [waxing] development with constantly accelerated river-bed erosion, or the reverse. For the rate of erosion, varying continuously both ways, assumes all possible values from a minimum to a maximum. Hence identical profiles will appear in reverse sequence in both series, so that any present profile may just as well belong to either.[3]

* W. Penck,[36] *Einrumpfung*: "Sie ist bis auf ihr theoretisches Endergebnis in allen Phasen durch konkave Hangprofile ausgezeichnet."

Destruction of Peneplains by Erosion

Dissection of a peneplain may generally be attributed to uplift, with the possible alternative, in cases where uplift appears to have been uniform, of eustatic withdrawal of the ocean to a lower level. Domed or broadly undulating uplifts are common, however, and dissection without uplift may result from lowering of the neighbouring land surface by down-warping, as pointed out by Philippson.[37] Should the central, higher part of a continental peneplain have the sea margin brought nearer to it, or have a steepened slope formed along its border, by subsidence of a down-warped or fault-bounded marginal portion without itself moving either up or down, it will be subject to dissection as though it had been uplifted. An example of this has been described in South Africa, where the headwaters of the short eastward-flowing rivers of Natal are encroaching on the inland peneplain of the High Veld. The distance down the Tugela River, in Natal, to the sea is only 200 miles, whereas westward to the sea by way of the Orange River the distance is 2000 miles. According to King[30] the migration of the continental divide westward, which involves dissection and destruction of the peneplain at the level of the High Veld, is due to an "effective drop in base-level . . . produced not by uplift of the land but by betrunking of the rivers". A former eastward extension of the African continent has sunk.

Though the lowering of part of a peneplain—along a fault, for example—will thus lead immediately to dissection and further erosional lowering of the remainder, there is no justification—as Baulig[3] has pointed out—for an assumption, such as has been made by some European authors, that the level of the lowered part of the peneplain is a base-level towards which the denudation of the remainder will proceed. The base-level is, as it was before, sea-level, whether earth movement has lowered part of the land surface or not.

Some dissection of an inland peneplain may be brought about also by climatic change, as in the case of plains of lateral planation, but river gradients are generally weak on peneplains, and probably no deep dissection or production of sharp forms of relief need be explained in this way. A hypothesis of changing climate ought to be considered, however, along with other possible causes of the development of "infantile" features, if such should be recognised on a peneplain.

Local dissection will begin on any warped peneplain wherever an earth movement steepens the general slope; but where quite uniform uplift or eustatic sinking of sea-level has taken place the lowering of base-level relatively to the land surface does not immediately stimulate renewed erosion and dissection of the whole surface.

The old-age processes of peneplanation continue their action unchanged in the early stages of the new cycle of erosion introduced by the upheaval; hence the central peneplain suffers no significant change of form, except that it becomes an older and older peneplain, in spite of being now in the infantile stage of the new cycle instead of in the senile stage of the former cycle. So it continues until news of the upheaval is brought to it by the retrogressive erosion of peripheral streams; then it is more or less sharply dissected. (Davis.)[19]

It is noteworthy that infantile profiles (as defined on p. 280) do not make their appearance in this case of an uplifted but as yet undissected peneplain. In spite of this, however, Davis[19] has taken the view that it is necessary, because of difficulties that otherwise will be encountered in the interpretation of the sequence of events, to rule that upheaval, or a lowering of base-level, at once interrupts the cycle throughout the whole of the region in which it is effective (and that "similarly a uniform depression should be taken as introducing a new cycle"). Another possible interpretation[3] is that the former cycle is still current and will remain current in any locality until the "news of the upheaval" is brought to it by erosion working headward along the river valleys, for only then will landforms of a new cycle begin to develop (Chapter XIX).

Peneplain Remnants

Remnants, large and small, of many uplifted peneplains still survive in dissected plateaux, where resistant rocks outcrop over wide areas* (Fig. 217), and as occasional flat-topped mountains and

* Most commonly these are areas of granitic and gneissic rocks. It has been noted in Australia, however, that, while some extensive plateaux formed by well-preserved peneplains have granite under them, there are relatively lowlying areas of small relief on other granite terrains, which are apparently due to rapid erosion selectively affecting granite. Browne[4a] suggests that certain granites have been more thoroughly decayed by chemical weathering down to the water table (which has been at a considerable depth) under a peneplain than have other rocks, and that, as a result of such weakening, erosion in a new cycle has reduced the granite areas to lowlands, though the peneplain of the former cycle survives on adjacent terrains of stratified rocks.

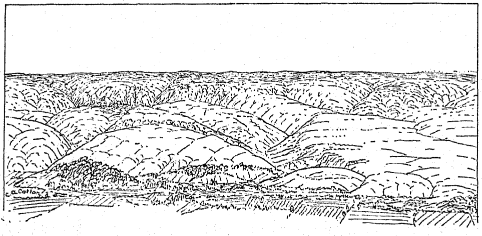


Fig. 217. The Longmynd, Shropshire. The plateau surface was cut by erosion (probably as a peneplain) across the varied structures of ancient resistant rocks.

ridges in submaturely dissected regions of mixed rocks. In such cases it may be possible to imagine a restoration of the originally continuous peneplain if a sufficient number of remnants of it survive, and such a restoration may show that, instead of remaining level as it was uplifted, the peneplain has suffered deformation.

Peneplain surfaces last for a vastly longer time on highly resistant rocks than on weak rocks or even those offering moderate

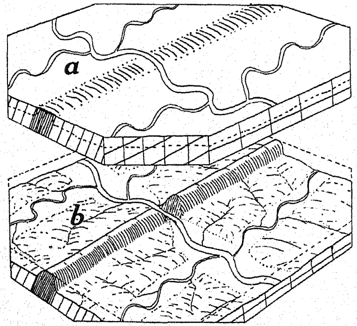


Fig. 218. An even-crested ridge on the outcrop of a resistant stratum preserving a remnant of the peneplain *a* at a later period, *b*.
(From *Geomorphology*, also by the author.)

resistance to erosion. Thus even-crested and flat-topped, though possibly narrow, ridges of the most resistant rocks may be found separating subsequent lowlands of quite small relief and considerable breadth developed in a later cycle or cycles (Figs. 218, 219). In the Appalachian plateau of the United States, for example, the "Schooley" peneplain is only submaturely dissected over a very large area in which all outcropping rocks are resistant; farther east, however, in the Allegheny ridges, it survives only on the even crests of subsequent ridges of the most resistant rocks (Fig. 219); while still farther east it may be recognised again as a more nearly continuous plateau on resistant rocks in the Piedmont belt.[27] This widespread

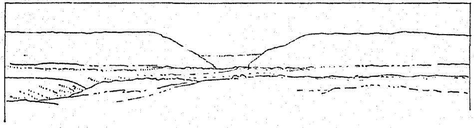


Fig. 219. Even skyline of the Schooley peneplain on a ridge traversed by the water gap of the Delaware. (From a drawing by W. M. Davis.)

and very thoroughly levelled surface, which evenly truncates the most resistant rocks of the region, and which was formerly ascribed to Cretaceous erosion, is now regarded as of much later date. Some investigators have come to the conclusion that its upheaval was accompanied by warping which converted it into an elongated dome diversified by smaller domes that are still recognisable in studies of the summit levels in those areas in which the peneplain is best preserved; and some of these have been mapped.[21, 48] Subsequent lowlands that have been excavated below the Schooley peneplain on the broad outcrops of the weaker rock formations (and also the sides of valleys, especially air gaps, through hard-rock ridges) exhibit relics of much less extensive peneplains that were developed in at least two (and perhaps more numerous) later and shorter periods of erosion[27] (Chapter XIX); and the summits of monadnocks that rise above the Schooley level seem to preserve residual fragments of a still higher and older peneplain.

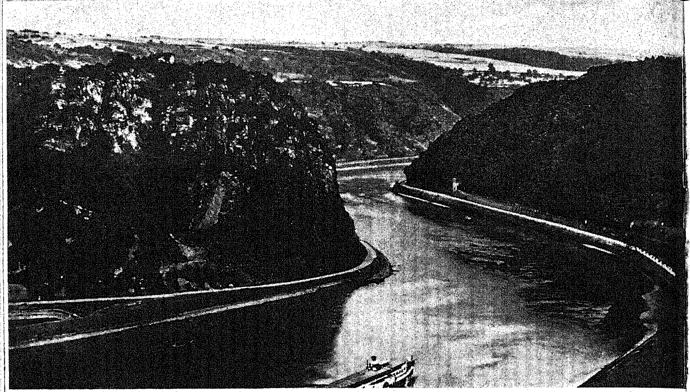


Fig. 220. Highland peneplain cut through by the gorge of the Rhine at the Loreley bluff.

Peneplains developed in bygone cycles — cycles which were terminated eventually by upheavals and by lowerings of base-level — are still preserved as remnants on many terrains of resistant ancient rocks in north-western and western Europe. These are found, for example in the mountains of Germany, including those that are cut through by the lower gorge of the Rhine[37] (Fig. 220), in the Ardennes, the Central Plateau of France, Brittany, the plateau of Norway (Figs. 221 and 221A), on the moors of Devon[43] and perhaps

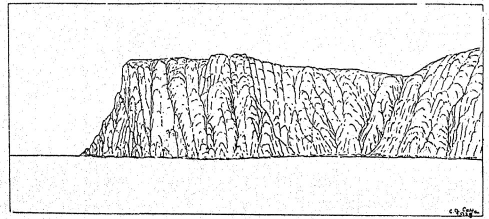
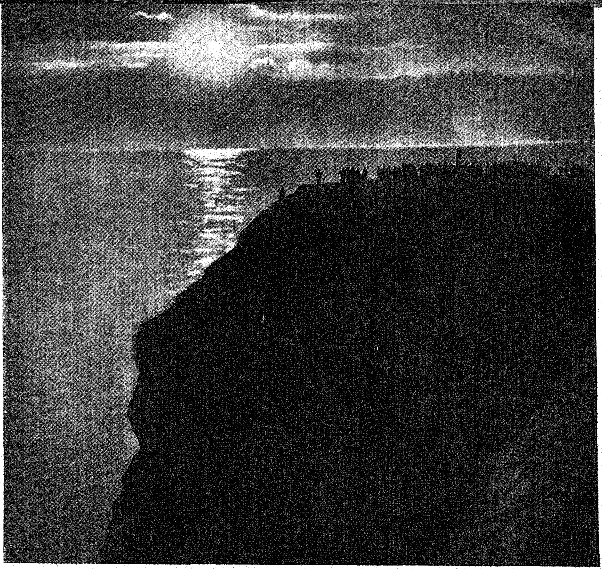


Fig. 221. The plateau of Norway, at North Cape.



Mittet, photo

Fig. 221A. The margin of the plateau of Norway, at North Cape, seen by the light of the midnight sun.

the uplands of Cornwall,[2a] at heights of 1500-2000 feet in Wales,[43] and at 2000-3000 feet in Scotland[35] (with another less continuous but well developed planation there at about 1000 feet). Parts of the European plateaux seem, however, to be ancient "fossil" erosion surfaces (Chapter XVII), some of them buried for a very long period though their re-exposure by erosion has taken place comparatively recently. The distinction of these from true peneplains that have never been lowered below base-level and covered is not always easy, and it is probable that some of these surfaces, which have been somewhat worn down by more recent erosion, have been at some stage re-made into peneplains. A fossil origin is suggested for the plateau of Norway—as a part of the very ancient and widespread fossil peneplain of Fennoscandia—and for at least some of the level upland surfaces of Britain. In particular, it seems probable

that there was a very extensive smoothly-worn floor truncating folded Palaeozoic rocks, over which Jurassic and still more widespread Cretaceous strata were laid down only to be later stripped away entirely over a large area.[28] Exposure of this floor would account for the semblance of a plateau, now tilted and somewhat warped,[7] that is produced by the accordance of levels exhibited by many summits in Wales, some of them flat-topped. This eastwardly-ascending dissected plateau was admirably described by Ramsay,[39, 40] who called it a "plain of marine erosion", ascribing its origin to wave work at the margin of a gradually rising and advancing sea in very ancient times. Some observers have regarded the higher mountains of the Snowdon group, in North Wales, as monadnocks that rise above an ancient peneplain, or perhaps residual islands that have escaped destruction by the ancient marine erosion; but Greenly[23] has drawn attention to the smoothly domed form of an up-arched erosion surface (now dissected) with which the summits of these mountains exhibit a close accordance of level. He has shown moreover that this surface, which was without doubt a product of Cretaceous erosion, was upheaved only in rather late Tertiary times, when it was stripped of a Cretaceous cover.

The theory that the broad "torsos" of resistant rocks in parts of Britain owe the smoothness of their skyline profiles largely to resurrection of a fossil erosion surface is not inconsistent either with a hypothesis of some more recent modification of the landscape form by peneplanation or with that of marine benching at successively lower levels which is favoured by Green,[22] Hollingworth,[24] and others.

A surface which Davis[15] long ago interpreted as a peneplain bevels the cuestas of Mesozoic rocks in eastern and south-eastern England. As it has since been interpreted by Wooldridge and Linton,[49] this surface, or part of it, has been finally planed by marine erosion and thinly coated with unconsolidated marine Pliocene deposits, which have since been almost completely washed away. It is definitely a product of late Tertiary erosion, however, and the surface over which the sea advanced in the Pliocene period must have been already practically a peneplain.

Records of ancient peneplains in various parts of the world were summarised by Davis[14] in 1911 as follows:

High standing, deeply dissected peneplains are described by de Martonne in the Transylvanian Alps; Daneš, Cvijić, and others have found lower standing peneplains in the Dinaric Alps. . . . The southern extension of the Ural Mountains is still a low-lying peneplain, undissected over large areas; but farther north uplift and dissection of what seems to be part of the same peneplain produces a topography of submountainous relief. The Tian Shan and the Pamir exhibit numerous and extensive highland peneplains. . . . Lofty highlands of erosion in the north-western Himalayas are described by Oestreich; Loczy and Filchner describe similar forms in Tibet. . . . Willis has given abundant description and discussion of high standing, dissected peneplains in the mountains of China. . . . Bornhardt, Uhlig, and Jaeger describe highland peneplains,

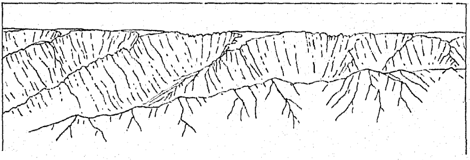


Fig. 222. The flat-topped Bural-bas-tau Range, in the Tian-Shan. (After a drawing by W. M. Davis.)

more or less dissected, in equatorial east Africa, Passarge and Hassert in south-west and west Africa. Keidel reports uplifted peneplains in the eastern members of the Argentine Andean massif. . . . Bowman describes a lofty peneplain in the Bolivian Andes. . . .

Nearly the whole of the surface of Australia is a great peneplain,[1] the development of which continued until late in the Tertiary, and large parts of it have suffered little modifications since because of the small magnitude of the uplifts that have affected it, though smaller parts, especially some near the eastern coast, have been considerably uplifted with faulting and warping, and are more or less thoroughly dissected as a result[44] (Fig. 60).

The Age of Peneplains

Probably all well-preserved (i.e. not thoroughly dissected) peneplains are of geologically modern origin, if we exclude consideration of such as have, at some stage of their history, been preserved by burial and long afterwards re-exposed by removal of a cover. Even

the great peneplain of central Asia (Fig. 222), which is preserved on the crests of the Tian-Shan Mountains and on the Pamirs at heights of over 12,000 feet, was developed, according to a reliable authority,[25] at the end of the Tertiary era; and Davis[13] has suggested that this is part of the peneplain that remains at a low level and undissected where it borders the Irtysh in Siberia. Where parts of extensive erosion surfaces of small relief are known or believed to be of greater age, the regions in which they occur have generally remained lowlying until the end of the Tertiary era, as was the case in the uplifted and dissected parts of the great Australian peneplain.[1] The significant date is the date of interruption of the major cycle of

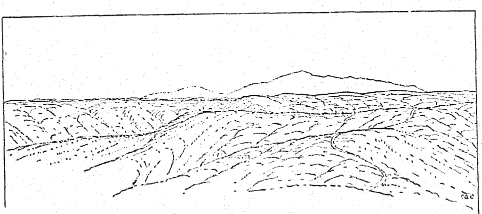


Fig. 223. The Rocky Mountain peneplain (about 10,000 feet above sea-level) with a high monadnock (Pike's Peak) standing above it. (From a photograph by Professor Douglas Johnson.)

erosion in which the peneplain was formed, however vast the anterior period may be during which it was already in existence at a low level, undergoing more and more complete planation. It is well to accept with caution some geological dates of origin, in some cases incredibly ancient—a favourite suggestion being Cretaceous—that have been ascribed to peneplains of which remnants still survive, though they are believed to have been continuously subject to denudation since uplift brought to a close the ancient period of their supposed formation; but "it seems only reasonable to suppose that any land surface of Cretaceous age continuously exposed to erosion since [upheaval in] Cretaceous time must have been long ago completely destroyed" (Douglas Johnson).

Revision has referred surfaces of supposedly very ancient development to much later periods of erosion, as in Africa, where vast

areas surviving as plateaux are referred now to Miocene peneplanation, while relics of earlier-developed landscapes are relatively scanty.[29, 45] Those parts of very ancient surfaces that have survived, if at all extensive, seem generally to owe their preservation to burial, and have been only recently exhumed. They belong therefore to the category of fossil erosion surfaces (Chapter XVII), and cannot be described as peneplains without introducing errors into the interpretation of geological history.

The peneplain that survives most extensively as plateau surfaces in parts of the Rocky Mountains[14, 32] (Figs. 130, 223, 239) is now ascribed[2] to a prolonged period of erosion extending from middle into very late Tertiary time, and even this comparatively recently developed surface has been widely mantled with thick alluvial deposits, the presence of which must have contributed to its preservation. In France, also, where extensive plateaux are parts of a peneplain developed in a Miocene cycle of erosion, much of this ancient surface of erosion has been long preserved as a fossil plain beneath a cover of Miocene strata that has only very recently been removed from it.

Duration of a Geomorphic Cycle

According to reliable authorities the time span of the Tertiary era was about sixty million years. A fraction of this apparently sufficed for peneplanation of average resistant rocks. It is of interest to glance at an attempt made by Davis actually to estimate in years the duration of a cycle of erosion. By comparing incipient erosion of beach features of the extinct Lake Bonneville with ridge-and-valley forms on which these rest, he estimated that the erosion of the latter had taken scores of times as long as the duration of the post-Bonneville epoch; but the ridges and valleys themselves had been eroded in detritus resulting from partial degradation of a fault-block mountain range, which must have occupied scores of times as long as the erosion of the valleys in the detritus. As complete destruction of the range will take many times longer, i.e. "many times longer than scores of scores of post-Bonneville epochs", the length of a cycle of erosion as estimated roughly by this method would be from 20 million to 200 million years.[17] The larger figure at least seems to be excessive.

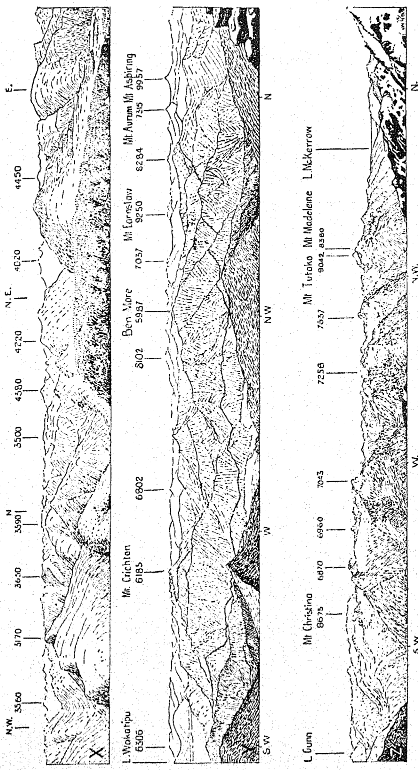


Fig. 224. Panoramas showing accordance of summit levels in western Otago, New Zealand. (After Benson.[4])

V. C. Browne, photo

Fig. 225. Accordance of summit levels is well marked in the nearer ranges, though not in those near the skyline; for the latter are large, unreduced tectonic blocks (shown in Fig. 286). View north-eastward across the ranges of the Southern Alps in North Canterbury and across Marlborough, New Zealand.

Peneplains in the Mobile Belts

It is not surprising to find the remains of well developed peneplains in those regions in which there is geological evidence of almost perfect stability of the earth's crust in the later geological periods, but one is inclined to accept with great caution similar evidence of prolonged still-stand in the crustal strips that have suffered strong deformation in late geological times. Relics of peneplains are known in most of these, however, being reported, for example, in the European Alpine region; the folds of the Jura Mountains are evenly truncated by an eroded surface.[5] Episodes of earth movement that have been accompanied by writhing and warping of the land surface have been separated generally by lengthy epochs of tranquillity. In New Zealand (situated in a mobile belt) peneplanation developed very widely over weak-rock terrains, notably in the district inland from Wanganui, at a very late date—Pleistocene—subsequently to the Kaikoura paroxysm of block faulting accompanied by folding that brought Tertiary deposition to a close, and in the vicinity of the city of Wellington a late mature to senile surface, possibly developed in the same late period, is represented by remnants on ridge crests of rather resistant rocks.[8]

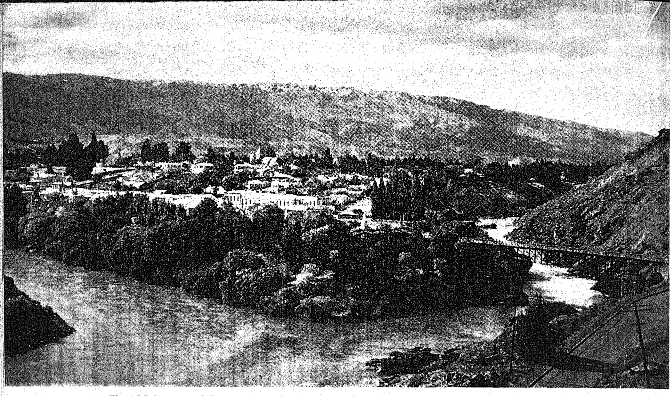


Fig. 226. Peneplain remnant on Mount Pisa, a fault-block mountain, near Cromwell, New Zealand.

In parts of the South Island of New Zealand—notably in Otago—there are relics of a very well developed peneplain that dates back to a pre-seismic late-Tertiary epoch of prolonged still-stand and erosion.[4] Farther west this surface seems to have suffered little distortion but only considerable upheaval, thereby becoming an initial plateau since dissected to make the high residual mountains of Fiordland (Fig. 224). It is there recognised now only in accordant summit levels, and similar evidence of up-arching of a well developed peneplain is found throughout a great part of the main range of the Southern Alps[46] (Figs. 225, 328). In Otago, however, this peneplain is less dissected, and, though dislocated by great displacements, it survives on the level tops of block mountains (Fig. 226).

Accordance of Summit Levels

Where no flat remnants of a peneplain actually survive, *accordance of summit levels* (Fig. 225) may indicate that such a surface has been dissected and destroyed by erosion; many peaks will still reach to about a common level, or to levels accordant with a domed or warped surface passing over them, though the top of each sharpened peak must have been lowered somewhat below the level of the initial surface. Some peaks that rise above the general level must, on the other hand, have stood out as monadnocks above the

A. J. Shearsby, photo

Fig. 227. The great Australian peneplain, near Yass, New South Wales, surmounted by a monadnock, the summit of which is a remnant of a much more ancient peneplain.

former peneplain. From such evidence it has been inferred, for example, that the peneplain referred to above extended formerly over the residual mountains in parts of the South Island of New Zealand, though in considerable areas no flat summits have survived its mature dissection.[46]

Even occasional monadnocks rising to equal heights above a peneplain may sometimes be interpreted, as is done in eastern Australia, as preserving in the level of their summits a trace of a more ancient peneplain[44] (Fig. 227), an inference there confirmed in some instances by the preservation of lava-capped gravels on the summits of the monadnocks. Flat tops on some monadnocks above the Rocky Mountain peneplain, in Colorado, seem also to be relics of another peneplain that is generally considered to be older.[32]

Mere accordance of summit levels, unless particularly well marked, in which case survival of at least a few flat-topped peaks may be looked for, does not indicate former peneplanation (or development of a plain of erosion of some other kind) with certainty, for it has been claimed that a rough accordance may be expected in the heights of peaks carved by erosion on mountains of massive or folded rocks in a single cycle.[9] Anticlines that are lifted to an exceptional height must tend to sink again isostatically. Also, mechanical erosion is most active on the highest peaks, and, provided that the resulting waste can slide away down steep slopes as fast as it is supplied by weathering, to be then removed by streams, differences in height must in this way be reduced; while from Gilbert's

law of equal declivities—the tendency to develop slopes of equal steepness—it follows that, if streams are evenly spaced and have cut downward to approach base-level, the ridges between them must be reduced to the same height. So it appears that a mountain range made up initially of a concourse of blocks and arches differentially elevated, the whole forming—as it probably would—an elongated dome with a very irregular surface, might tend to develop such a measure of accordance of its summit levels that it would resemble the mountains carved by erosion from the smooth dome of a warped, uplifted peneplain.

Another possible cause of accordance of summit levels, and even of the development of an extensive upland surface of small relief independent of the general base-level, has been pointed out by Lawson. This is the exposure of a structural surface of relatively resistant rocks, such as the more or less regular, but not quite smooth, upper surface of a batholith, when erosion has removed from it a roof of weak sedimentary rocks. Lawson[31] suggests this origin for the highest, or "summit upland", surface of the granite terrain of the Sierra Nevada of California.

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CHAPTER XVII

Resurrected Fossil Land Surfaces

A FOSSIL IS A THING "DUG UP", AND FOR THE PALAEONTOLOGIST THE term "fossil" signifies some part or some trace of an animal or plant buried in the distant geological past and either dug up or exposed by erosion very recently. A *fossil erosion surface* is, in a similar way, an erosion surface, whether young, mature, or old, and whether produced by normal subaerial erosion or other agency, that has been buried beneath a cover of sedimentary deposits and long afterwards exposed to view again by renewed erosion. Some fossil erosion surfaces can be seen only in quarries, cuttings, or natural sections, where the covering strata still lie on them; but others have been partly *resurrected,* or *exhumed,* owing to stripping away of a cover that is relatively very weak as compared with the resistance offered to erosion by the undermass, so that parts of an ancient relief, perhaps very little modified by the erosion that accompanies their resurrection, again appear in the land surface after having been buried for geological periods.

FOSSIL EROSION SURFACES

An ancient landscape of hilly relief has been exhumed in places in the North-west Highlands of Scotland after having remained buried since late pre-Cambrian times. It was developed on hard gneissic rocks, while its cover consists of relatively weak sandstone (Fig. 228). As is commonly the case where mature (i.e. hilly) landscape forms have been buried, the cover is of non-marine origin. Similar resurrection of a hilly surface developed in the Triassic period on very ancient rocks is taking place in Charnwood Forest, in Leicestershire.

In South Africa there has been much exhumation of ridges of a diversified landscape that was developed in the Carboniferous period and somewhat later.[16]

West of the Vaal River . . . the Kaap Plateau, the Asbestos Mountains, and Kuruman Hills represent features of that age apparently but little modified by erosion since the removal of the cover. . . . The Witwatersrand is a pre-Karroo feature. . . . The Central Transvaal is also a region from which the Karroo cover has recently been stripped.[19]

Another example of a surface of considerable relief exhumed by removal of horizontal covering strata has been described from the "central plateau" of Morocco, west of the Atlas Mountains, though in this case the resurrected surface, described as the post-Hercynian "peneplain", has been "modified somewhat" by later erosion.[20]

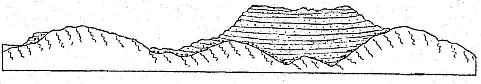


Fig. 228. A surface of late pre-Cambrian erosion emerging again as a cover of Torridonian sandstone is stripped from it, in the North-west Highlands of Scotland. (After a published section.)

In compound structures, where a cover of relatively young sedimentary formations rests unconformably on an eroded undermass, a lapse of time—in some cases an enormous interval—has occurred between the formation (and commonly also deformation) of the undermass and the ensuing submergence (or combination of other circumstances) that has led to the deposition of the cover. It is during this time interval that deep erosion, followed in many cases by more or less perfect planation, of the undermass takes place, preparing a floor on which the cover subsequently rests. Such is the history of the origin or most fossil erosion surfaces.

Fossil Peneplains

Young and mature surfaces are only rarely found buried: fossil surfaces are commonly plains of erosion, and sometimes clearly peneplains on which an ancient soil may still be recognised, with vestiges of vegetation, covered by gravels of terrestrial origin, though these are generally followed by marine sediments. In other cases, however, marine sedimentary formations rest directly on the eroded surface of the undermass, which consists of fresh rock evidently planed by marine erosion. Even in such examples the surface prior to submergence has in most cases probably been a peneplain, for

during progressive submergence of a land surface *of low relief* the waves of the advancing sea could break up and remove the deeply weathered soil, exposing and planing the underlying unweathered rock. In many profile sections exposing the base of sedimentary strata these may be seen lying unconformably on a flat floor that was horizontal at the time the beds were deposited, as is shown by

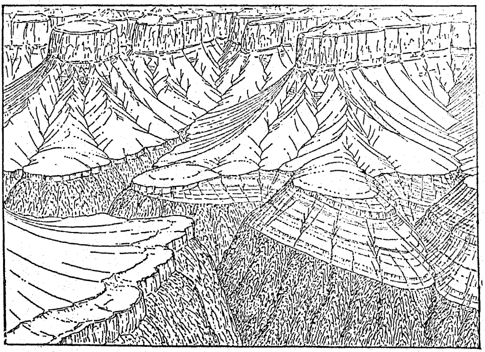


Fig. 229. The "Algonkian wedge", with fossil plains below and above it, in the Grand Canyon of the Colorado River. (After Davis.)

the fact that it is now parallel to their stratification. If this relationship of cover to undermass is seen in a number of scattered sections, it is known that the fossil plain underlying the cover is of wide extent.

One of the best-known regions in which fossil-plain profiles are thus clearly revealed in many natural sections is that intersected by the Grand Canyon of the Colorado and the canyons of some tributary rivers (Fig. 229). A cover of Cambrian and other Palaeozoic rocks, still quite horizontal in spite of their advanced age, lies on a floor that has been interpreted as a buried peneplain, for, instead of being quite plane, it rises in low monadnocks that interrupt the continuity of the lowest member of the Cambrian cover, which is a sandstone.

Fossil peneplains, and fossil erosion surfaces generally, are not necessarily found in their original attitude: some have been tilted and warped, or folded, along with the strata that lie on them. Where, as is very commonly the case, the beds of the cover were laid down horizontally on a horizontal floor, the parallelism of at least the lower beds of the cover with the floor has been retained, though both are warped or tilted. In some of the sections revealed in the walls of the Grand Canyon (Fig. 229) a series of beds older than the Cambrian and forming part of the undermass beneath the Cambrian peneplain (the strata of the "Algonkian wedge") appear, and are also well-bedded formations—tilted, however, in this case—and these have beneath them still older, crystalline rocks, on which they lie unconformably. Here the contact is made at a floor that is another fossil plain, tilted along with the beds that rest upon it, and more perfectly planed by ancient erosion than the Cambrian fossil plain. So it seems that parts at least of this more ancient surface must have been levelled off finally by the waves as the sea advanced over it to deposit the pre-Cambrian strata now preserved in the "wedge",[12] though some parts, on which weathered rock and ancient soil have been found, escaped this marine levelling.

Resurrection, or Exhumation, of Fossil Peneplains

Fossil plains have a chance of emerging again, or being resurrected, as surface forms if the cover overlying them is relatively very weak and is, therefore, readily removed by erosion from such parts of the fossil surfaces as are raised by modern earth movements above the base-level—below which, however, they will continue to be preserved indefinitely. Only such surfaces can be extensively exposed as have escaped severe distortion accompanying folding of the cover. A crumpled surface such as that illustrated in Fig. 230, even if stripped of a weak cover, would be destroyed by erosion as it emerged.

Extensively resurrected fossil peneplains, in various stages of destruction by erosion and in many places traceable only in isolated remnants, are now recognised in various parts of the world. In many cases "peneplains" formerly described as though they had survived, or, at least in parts, escaped complete destruction, though continuously subjected to subaerial erosion following uplift in Cretaceous or early Tertiary times, have more recently been given

a more easily credible interpretation as fossil surfaces comparatively recently resurrected. In Chapter XVI reference has been made to the possibility that some of the high plateau remnants in Britain owe their flatness to a comparatively recent stripping of cover from a Mesozoic floor. The "peneplain" of Fennoscandia has also been explained as an extremely ancient surface resurrected.[23] It must be kept in mind, however, that dissection to some depth, followed by peneplanation, may have taken place on some such ancient resurrected surfaces since the fossil landscapes were stripped of their

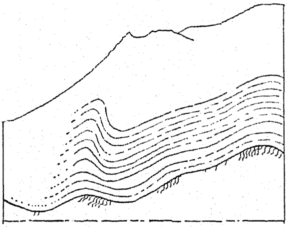


Fig. 230. Folds in Table Mountain sandstone and the floor on which it lies unconformably, Worcester, South Africa. (Drawn from a photograph published by Rogers and du Toit.)

protective cover. (As has been stated in Chapter XVI, this is the process of peneplanation—in this case re-peneplanation—must economical of time. As a hypothesis it may be necessary to consider also the process of old-from-birth re-peneplanation as a possibility.)

Meyerhoff[21] deprecates what he describes as

the dodge of pushing back into the remote past in an effort to explain such erosional forms as the Laurentian Upland [of Canada]. It has been argued that the Laurentian surface is a Lipalian peneplain formed in pre-Upper Cambrian time and re-exposed by stripping. When we come to analyse this suggestion, we can go into Wisconsin and northern Michigan and discover that here the pre-Cambrian surface was rugged.

There are many genuine cases of resurrected fossil plains and peneplains, however. In south-eastern England[24] facets of two fossil

surfaces have been recognised, the one Eocene (or pre-Eocene) and the other Pliocene (or pre-Pliocene). In the Central Plateau of France the land surface is now considered to be in great part a peneplain of pre-Miocene age that has been extensively buried under a cover of late Tertiary strata and resurrected later; and bordering this there is a strip of a much more ancient (post-Hercynian) surface resurrected from beneath Mesozoic strata.[1] Farther north in western Europe a wide extension of late Tertiary deposits is known or suspected to have been present, covering areas that are now upland plateaux of resistant rocks[3] alternatively regarded simply as continuously emergent parts of the great west-European peneplain, though many facets of the land surface that are definitely parts of ancient fossil surfaces have been recognised.

In eastern North America the Fall Zone peneplain, of Johnson,[18] is known in a resurrected strip. In South Australia resurrected relics of a fossil surface are present in the landscape at least as facets, and perhaps on the greater part of a faulted plateau, in the Mount Lofty Ranges[17, 23] (Fig. 282). Fenner has described these as "the prevailingly highly resistant Cambrian and pre-Cambrian complex . . . , which was planed down to a remarkably widespread level surface in pre-Miocene times." In east-central Africa the emergence of a fossil plain from beneath a Cretaceous cover is described by Dixey.[16]

Resurrected Fossil Plains in New Zealand

In New Zealand extensive strips of the land surface in Otago and other districts of the South Island and smaller areas in the North Island are resurrected parts of fossil plains.[4-11] The majority of the upland surfaces so interpreted in this region have not remained horizontal, but are tilted, arched, and even folded in gentle undulations. Some horizontal, gently tilted, and even, in exceptional cases, quite strongly tilted portions of the fossil plains, though stripped of weak cover "as mud is washed from a board", are but slightly dissected, while others have been destroyed by mature dissection, especially where strongly tilted or corrugated or otherwise deformed during uplift.

In the southern part of the South Island an extensive peneplain began to be covered by sedimentary deposits both of land and

marine origin in the late Cretaceous, but peneplanation of some parts of the region continued until early Tertiary times before burial took place. After being comparatively recently uptilted and resurrected smooth slopes of the fossil peneplain thus developed and stripped have escaped dissection to a remarkable extent. Some of these are of appreciable steepness, more particularly in the semi-arid district of Central Otago,[7, 8] where not only is the annual rainfall low but rain is light and generally well distributed through the year, though some local cloudbursts have been reported. Whether the climatic conditions have contributed appreciably to their preservation or not, it is true that in this district smooth tilted strips are so stable, or so long-lived in the landscape, that they constitute important and conspicuous features that make up a considerable proportion of the uplands and highlands. The differential uplifts of the ranges on which these slopes have been exposed and survive cannot be regarded as of very recent occurrence, but must be ascribed to a period of uplift and deformation at the end of the Tertiary era, which has been followed throughout most parts of New Zealand by an enormous amount of erosion. On the other hand, there is no reason why it should be thought, on *a priori* grounds, that the uplifts of various ranges were quite simultaneous. The cover that has been stripped away has generally been very weak, and it has probably long ago been removed from most of the exposed surfaces, but it must be true that some of the slopes have been exposed to erosion, and subject to dissection, much longer than others. The delay of dissection on the slopes longest exposed, whichever they may be, has resulted in an accumulation of similarly developed forms, or, to put it in another way, indicates the stability, or longevity, of forms at this stage of development under the conditions here prevailing. Such stability marks these forms as a definite type, and calls for investigation.

Special resistance to erosion in the undermass rocks of the Otago district cannot be appealed to. The commonest material is a mica schist that cannot be regarded as an exceptionally resistant rock, and somewhat shattered greywackes similar to those of the mountain axis throughout New Zealand underlie some of the slopes. Granted that the rocks underlying a tilted fossil plain—or, indeed, any other tilted surface—are somewhat resistant to erosion, though perhaps not exceptionally resistant, the next important condition making

for long preservation of slopes in an undissected condition after exposure seems to be that there shall be little run-off. It is well known that slopes of very absorbent, even though unconsolidated materials are relatively indestructible, and the paradox has been announced that "gravel is a resistant rock". In the case of the resurrected plains referred to, however, the surface is not very absorbent, and the smallness of the run-off results from the nature of the climate, already described. The initial slope must also be smooth and uniform, so that the consequent drainage on it, or drainage superposed on it from a cover on which it has been consequent, shall run off as numerous small parallel streams among which none is likely to become a master.[7]

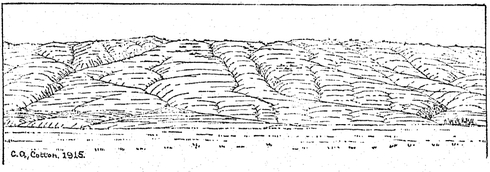


Fig. 231. The north-westward slope of Rough Ridge, New Zealand, a resurrected portion of a fossil erosion surface that descends in the foreground beneath covering strata.
(From *Geomorphology*, also by the author.)

The back slope of Rough Ridge (a tilted uplifted block) is one of the best examples of these well-preserved resurrected inclined surfaces in New Zealand[8] (Fig. 231). There seems to be in this case such an agreement between the slope of the surface and the volumes of numerous small streams that drain it that the latter have become graded without being deeply incised in the surface, and it is obvious that any smooth surface, horizontal or inclined, that is traversed by shallow ravines which are no longer being deepened, and which do not contain perennial streams sufficiently large to be capable of lateral corrasion, will escape rapid dissection, and so be a stable form. As the ravine sides become graded, the sharp shoulders which at first bound the flat doabs between such ravines will early disappear, and so in the stable condition of the slope these interfluves are

broadly convex, subdued forms; but the inclined crestlines of the flat spurs, which they have become, are accordant with one another, allowing the eye to reconstruct the somewhat worn tangent surface of the emergent tilted plain.

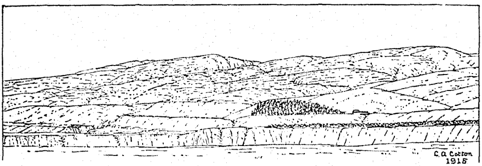


Fig. 232. Resurrected portion of an inclined fossil plain forming the western slope of the Hunter's Hills, New Zealand. In the middle distance the slope of the fossil plain descends beneath marine covering strata in the valley of the Waihao River.

An extensive resurrected surface on the Hunter's Hills (South Canterbury, N.Z.), with similar slope to that of Rough Ridge, has streams more deeply incised in it[5] (Fig. 232), perhaps because of more abundant rain in that district; and in north-west Nelson, which is a wet district, similar slopes are considerably dissected.[6] There, however, particularly well-preserved resurrected surfaces *that have*

Fig. 233. Fossil plain of the Gouland Downs plateau, New Zealand. An undermass of very resistant rock has been stripped of cover and is experiencing incipient dissection.

remained horizontal occur as rather extensive plateaux, notably the Mount Arthur Tableland and that known as the Gouland Downs, each at an elevation of about 3000 feet. The Gouland Downs plateau (Figs. 233, 364) is very slightly undulating, in part swampy, with a sour waterlogged soil, and is drained by streams that are sluggish and but little below the plateau level near their headwaters, though downstream they are beginning to cut deep V-shaped valleys. Though this is a very wet district, the presence of particularly

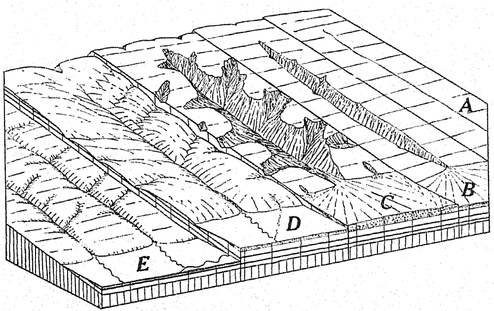


Fig. 234. Development of the surface of a gently tilted strip, the land surface of which is initially a sloping plain on a weak cover lying over a resistant undermass with planed surface. *A*, initial form; *B*, *C*, and *D*, intermediate sequential forms; *E*, stage at which a fossil plain has emerged as a stable form.
(From *Geomorphology*, also by the author.)

resistant slates and quartzites in the undermass has resulted in delaying the destruction by erosion of those parts of the resurrected surface that are nearly level. Resurrection of the fossil surface is well attested on the Gouland Downs plateau by survival of a few small mesas, or "hums" (Chapter XXIII), which are remnants of a cover of Tertiary limestone in course of removal in solution (the bush-clad "islands" in Fig. 364).[6]

Conditions of Survival of Fossil Plains in the Landscape

Among general conditions favouring conspicuous survival of resurrected plains obviously the first essential is that the undermass shall be contrastingly resistant as compared with the unconformable cover that may be removed from it. Erosion of the cover is hastened

by tilting of strips or earth blocks during differential uplift; but survival—as contrasted with progressive destruction by dissection as it emerges—of the surface of the undermass itself can take place only when the strip or block is tilted at a moderate angle, the permissible slope being somewhat steep, as discussion of some examples has shown, in a dry climate with well distributed rainfall. On the surface of a compound block with uniformly weak covering strata uplifted with tilting (Fig. 234) numerous consequent streams will come into existence, and if the tilting is uniform these will be approximately parallel and closely spaced, and throughout the dissection and degradation of the cover (Fig. 234, *B, C, D*) the stream pattern may change but little. Degradation of a uniformly weak cover will take place rapidly (though, of course, it will be necessary in applying the analysis to special cases to take into account erosion on covering beds of varying resistance). When, however, the streams cut through the cover and are superposed on the resistant rocks of the undermass, their vertical corrasion is checked and becomes very slow. After the streams have become superposed and the upland is maturely dissected, the relief of the surface, previously increasing, is reduced again as the interfluvial strips waste away. Even if the streams, or some of them, have become graded without cutting through the cover in the early stages of dissection, after the cover has been largely removed from the higher parts of the area they will be forced to degrade and will become superposed. Later, when the removal of the cover is nearly complete, all the streams will be incised to some extent in the undermass. In the resistant rocks of the undermass, however, the ravines will for long remain V-shaped, with convex side slopes, *simulating* youth, while on the spurs of the upland, between the streams, flat areas will survive, where the ancient eroded floor has been stripped of its cover (*E*; see also Figs. 231, 235). This stage will be attained earliest at the middle parts of even slopes, for there stream corrasion has deepened the valleys most; upstream and downstream from such points, owing to smaller depth of stream corrasion, undissected interfluvial areas will be larger and survive longer.

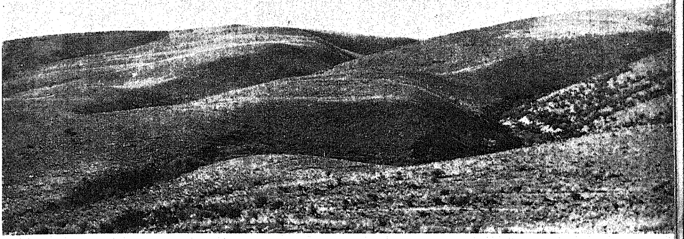


Fig. 235. A narrow tilted strip of resurrected fossil plain, showing the bottle-neck valleys of superposed consequent streams incised to a shallow depth below the flat surface, near St Bathans, Otago, New Zealand.

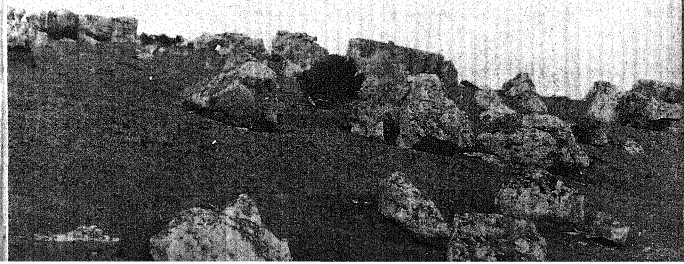
Distinction from Peneplains

In the New Zealand examples that have been described there is good evidence of their origin as resurrected fossil plains: either the surface slopes down so as to plunge beneath similarly inclined beds of the cover still resting on it in an adjacent depression, or outliers of the cover still survive here and there on the plateau or upland surface.[8]

On the plateaux of the Otago province, *sarsen stones* also lie about.[8] These are relics of some exceptionally resistant bed in the cover that has been broken up as softer material on which it formerly rested has been washed away. The fragments which, though generally reduced by long-continued weathering to small dimensions, still litter the surface of the exposed undermass on the Otago

Fig. 236. Sarsen stones lying on part of the little-dissected surface of the Rough Ridge fossil peneplain (Fig. 231), New Zealand.

Professor Douglas Johnson; photo



plateaux, consist of quartzite from well-cemented layers or lenses in the cover of quartz gravels. In a few places, where the sarsen stones are exceptionally large, they are very conspicuous (Fig. 236); but much more numerous and widely scattered smaller stones testify to the former presence of a widespread cover. Survival of such sarsen stones does not, however, prove that plateau surfaces on which they now lie are parts of a fossil plain; for quartzite is so resistant to weathering that they might survive while a peneplain was in course of development below the floor of the original cover, either with or without an intermediate phase of resurrection of the fossil plain forming the floor. The sarsen stones and "grey wethers"

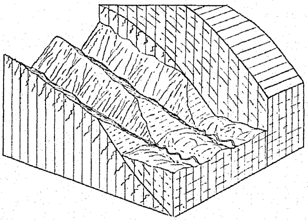


Fig. 237. Dissection of a rather steeply sloping fossil surface by vigorous streams.

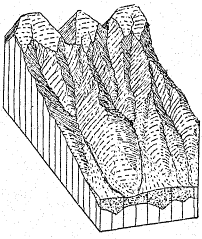


Fig. 238. Dissection of the middle of a slope, with survival of flat remnants at its top and bottom.

of the South of England and the Ardennes have survived in a similar way from a former cover. Though those of the south of England are derived from a cover of Eocene age, their presence does not prove any plateau surface on which they lie to be the Eocene floor resurrected; but quite large areas of this floor have been exposed by removal of the cover.[24]

Dissection of Inclined Surfaces

The survival of irregularly or slantingly uplifted plains, whether of fossil, peneplain, or other origin, must be regarded as somewhat exceptional, depending on special conditions such as have been suggested in this chapter, which reduce the available relief. In more commonly occurring circumstances surfaces strongly warped or tilted during uplift are shortlived. If, owing to abundant rainfall,

to steepness of initial slope (Fig. 237), or to initial irregularities of the uplifted surface that have resulted in concentration of consequent drainage into large streams, the graded profile for the dissecting streams lies far below the uplifted surface, mature dissection will not be long delayed. Remnants of the stripped surface may long survive on the ends of spurs, however, between bottle-necked ravines on either side that are not cut far below it (Fig. 237), and a strip at this level may be almost continuous if the dissecting valleys are widely spaced, perhaps having been reduced in numbers by abstraction in the struggle for existence. At the top of a slope that is sharply cut off in that direction, perhaps by the scarp of a faulted block, there is not much concentrated wash, ravines are not deeply cut, and another nearly continuous strip may survive (Fig. 238), possibly even capped by residuals of the cover.[6] Examples of such features are found in New Zealand, in which long, accordantly sloping, parallel spurs from a mountain range of tectonic origin suggest reconstruction of a smooth sloping surface above them which has been maturely dissected. Of this nature, for example, are the northwestward slopes of the Seaward Kaikoura Range[4] and Kaikoura Range (Fig. 179A) and the eastern slope of the Pikikiruna Range.[6]

Intersecting Peneplains

Occasional association of fossil plains, some resurrected and others merely observed in profile, with remnants of peneplains of later development necessitates consideration of the problems presented by "intersecting peneplains". Two fossil erosion surfaces of different ages may intersect and be observed in profile sections, as exemplified in the "Algonkian wedge" of the Grand Canyon section (Fig. 229); and many examples may be found of intersection of a relatively young summit peneplain, generally little deformed, with profile sections of an inclined or folded fossil plain, or with more or less discontinuous strips or facets of it, resurrected and emergent as a surface feature (Fig. 239). A notable example of such intersection is present in the Piedmont province of the eastern United States, where, at the Fall Zone, Johnson[18] has differentiated facets of an inclined resurrected surface (termed by him the Fall Zone peneplain) from the more nearly horizontal upland overstretched by the Schooley peneplain. Another example is the intersection in

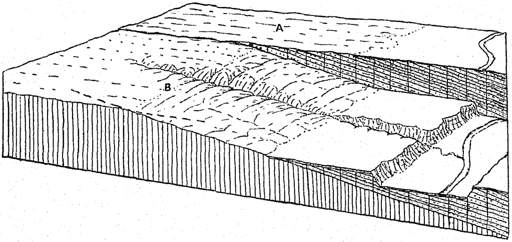


Fig. 239. Development of intersecting peneplains. A horizontal peneplain that has not been buried intersects an inclined fossil surface that has been partly resurrected. (From *Geomorphology,* also by the author.)

south-eastern England of the upland peneplain of late Tertiary development with sloping facets of the resurrected surface from which Eocene strata are in course of removal.[24]

Where, in such cases, a fossil plain is extensively exposed by erosion, it may be difficult to distinguish between isolated parts, or facets, of this ancient resurrected surface and the newer peneplain that intersects it. In the central plateau of Morocco, for example, Lawson records that "the exhumation of the old pre-Permian surface has produced a post-Alpine peneplain which in part happens to almost coincide with the post-Hercyninan one".[20]

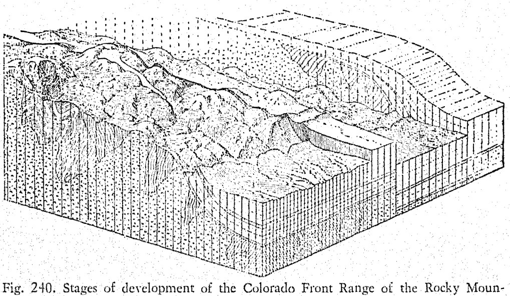


Fig. 240. Stages of development of the Colorado Front Range of the Rocky Mountains. Details are omitted, and only the most extensive erosion surface (the Rocky Mountain peneplain) is shown truncating the highland. (After W. M. Davis.)[13]

Fig. 241. Dissected margin of the plateau of south-eastern Otago, New Zealand, which is in part an unevenly uplifted peneplain but incorporates facets of a resurrected (Cretaceous) peneplain, at Hillend, near Balclutha.

A complex of landscape forms in which intersection of a superficial peneplain with a fossil erosion surface occurs was termed a *morvan* by Davis, who took the name from the Morvan plateau, in France. An example of a morvan that has been described in detail by Davis is the Front Range of the Rocky Mountains, in Colorado (Fig. 240).[13, 14, 15] In this case the morvan explanation stresses the modern age of the Rocky Mountain peneplain as compared with the floor underlying the Mesozoic strata arched up over the range and preserved along its monoclinal front. In any morvan the rocks have compound structure, with an undermass planed by erosion and over this an unconformable cover or overmass; the whole compound mass, after being tilted or deformed by folding, has had a peneplain developed across it; and later erosion has taken place, stimulated by uplift, resulting in dissection and partial destruction of the peneplain. In simple types of morvan the summit peneplain has suffered no deformation beyond doming or a limited amount of warping that has accompanied its uplift, but further complication may result from less regular uplift.

The eastern part of the Otago district of New Zealand, from which examples of resurrected fossil-plain remnants have already been described in this chapter, is a somewhat complex morvan. Here

the compound mass has been reduced to a peneplain after the occurrence of a possibly pre-Pliocene movement of uplift accompanied by slight deformation, and, after a long rest, has suffered another and more severe deformation at the initiation of the present major cycle of erosion.[2] Thus the very extensive plateau of eastern and south-eastern Otago (Fig. 241), broken by faults and somewhat warped and in places thrown into irregular undulations, is in parts a peneplain, though elsewhere a resurrected fossil plain; and in many places it seems impossible to distinguish between these intersecting surfaces. At some localities the younger peneplain is buried beneath lava flows. Besides appearing in profile section in some lava-capped buttes and small mesas it forms the floor on which rest the thick lavas of the Dunedin massif, and here both the lava flows and the floor on which they rest are quite strongly folded. The lavas overstep successive strata of the cover and lap over thence on to the undermass (Fig. 242).

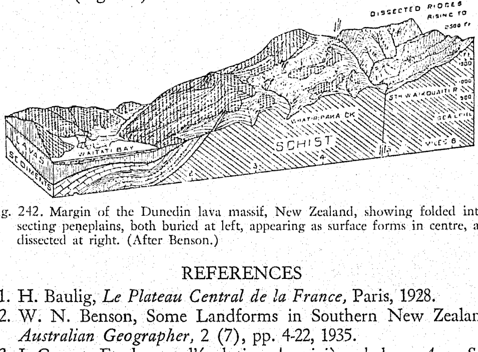


Fig. 242. Margin of the Dunedin lava massif, New Zealand, showing folded intersecting peneplains, both buried at left, appearing as surface forms in centre, and dissected at right. (After Benson.)

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CHAPTER XVIII

Effects of Uplift and Warping

THE COURSE OF THE NORMAL CYCLE OF EROSION MAY BE CUT SHORT at any stage by *accidents* and *interruptions* (as Davis has called them) of various kinds. Some minor modifications of the normal cycle that may result from small changes of climate have been noted in earlier chapters. Greater changes than these rank as accidents, such as refrigeration, bringing on glacial conditions, and the change to extreme aridity, introducing a complex of erosive processes working independently of base-level. Such accidents, and also volcanic outbreaks, which bury pre-existing landscapes, terminate the slow and orderly succession of normal events such as have been outlined, and introduce special landscape types. Discussion of special forms of the landscape developed as the results of climatic and volcanic accidents is beyond the scope of this book.

INTERRUPTING MOVEMENTS

Interruptions of the cycle, which must be considered now, are due to substitution of one base-level for another—i.e. to a movement of the base-level plane to a new position in the land mass either as a result of an actual rise or fall of ocean level or because the part of the land we are concerned with has moved while the level of the ocean surface has remained approximately as it was. Small changes in the relative levels of land and sea, of which many shorelines give evidence, are negligible in the long run if they are merely oscillations about a mean position. If, on the other hand, they are cumulative in one direction, the result is that the former base-level, which may for long have controlled the development of landscape forms, is replaced by another.

Base-level may have simply moved parallel to itself, up or down. If due to earth movement, such a change of base-level is really a special case,[12] though perhaps not quite so rare as has been supposed[3]; for earth movements generally involve some

warping or tilting of the land surface. It is probable, however, that many movements of base-level have been brought about by upward (positive) and downward (negative) movements of the ocean level of considerable magnitude. The changes of base-level thus brought about are termed "eustatic". There have certainly been very considerable floodings and regressions quite recently ("glacio-eustatic") as the continental glaciers of the Ice Age have melted, re-formed, and melted again repeatedly. The most recent positive movement of base-level due to this cause is estimated at about 300 feet. Earlier and perhaps much greater fluctuation of ocean level seems to be attributable to changes in the capacity of the ocean basins—such as might be caused, for example, by the building in the Pliocene period of archipelagos of huge basaltic volcanoes in the central Pacific region and the deep submergence of these a little later when their foundations gave way under the superposed loads.[26] Just what "volcano-eustatic" effects would follow these events might be debated, however.

Quite another case, and one that has been considered by Davis,[12] though not by Baulig,[3] as the more general case, is that in which the land, and with it the surface that was formerly the base-level plane, has undergone some deformation, and a new plane of base-level intersects the former one, which is now a tilted, warped, folded, or fault-broken surface. The same interrupting disturbance may result in an upward (positive) movement of base-level in one district and a downward (negative) one in another, such movements being, of course, relative to the land mass and not necessarily upward and downward in the sense of increasing or diminishing the distance from the centre of the earth. It is often convenient to speak of negative movement of base-level as emergence of the land, and of positive movement as (partial) submergence.

It is sometimes necessary to take carefully into consideration the effects of erosion of the land and also of aggradation that go on during the progress of slow movements, or of a slow succession of small movements (Chapter XIV). Commonly, however, when studying their effects in regions of somewhat resistant rocks, one may safely assume that interrupting earth movements and eustatic changes of base-level take place rapidly as compared with the rate

at which erosion works. Experience in matching deduced forms with actual landscape examples also teaches that movements, or spasms of movement, are separated by relatively long rests, or still-stands.[1]

As a result of the change in the position of base-level the former cycle of erosion has been cut short, and a new cycle is thus inaugurated, which runs through at least some of its stages in the period of still-stand that ensues. Though of the same general type, the landscapes of successive cycles may differ considerably in details. Adjustment to structure, in particular, may be expected to approach perfection only in a succession of cycles, proceeding vigorously only in the early stages of each cycle, in which streams are deepening their valleys and extension of these or development of new valleys by headward erosion is possible.

The assemblages of landforms that are to be regarded as characteristic of interruption are those in which a new-cycle landscape is, as it were, overprinted on the older landscape of the former cycle, considerable areas of the actual surface being attributable to erosion in each cycle. In the descriptions given in Chapter XVI of uplifted and dissected peneplains the concept of landscapes composed of erosional forms developed in successive cycles has already been introduced. Some parts of the land surface have been emergent and subject to erosion for vast periods and have been upheaved from time to time, so that very great thicknesses, perhaps miles, of rock have been removed from them. They have passed through many cycles, but traces only of the later, perhaps only of the latest, of these will be found in their landscape forms.

Where denudation has not removed a very thick layer in more recent cycles of erosion it is only in coastal areas that all traces of landscapes developed in earlier cycles have been obliterated.

The record of earlier erosion must be sought far inland near the present headwaters of the streams, where isolated residuals of earlier plane surfaces have been preserved from dissection and where hard ridges that have preserved their original surfaces during the peneplanation of adjacent soft rocks retain in a more or less ephemeral way the records of earlier erosion in the form of wind and water gaps. (Knopf and Jonas[21]).

Rejuvenation and Composite Landscapes

A cycle may be interrupted long before the landscape has become senile, and a *composite* landscape—i.e. one exhibiting "composite topography" (Davis), or forms developed in two (or more) cycles—quite commonly comprises summit forms that are relics of a partially destroyed mature landscape. If a cycle has been interrupted at

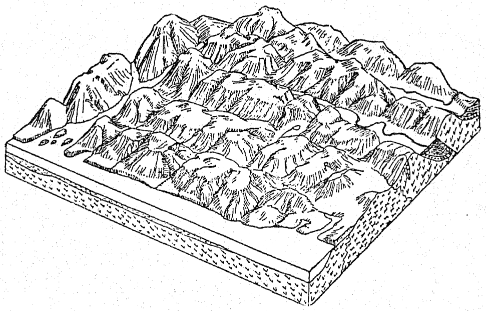


Fig. 243. Composite landscape forms of Vancouver Island, resulting from "mature dissection of an uplifted subdued surface". (After Clapp.)

the stage of maturity, its mature forms may be seen in course of replacement by somewhat younger forms of a new cycle, more advanced development of which will eventually destroy all traces of the mature summits, the landscape then ceasing to be composite. The gradual replacement of landscape forms of an interrupted cycle by young forms of the cycle that succeeds it is termed *rejuvenation* (Davis), and a composite landscape may also be described as rejuvenated (Figs. 243-7). A characteristic feature of rejuvenated landscapes is the *shoulder,* or break of slope, separating the gentler slopes of an older landscape above from steeper and younger valley-sides below.

Rejuvenation in the European Alps has been described by Brückner[4a] and, in the following words, by A. Penck:

The whole surface of that mountain region was in a state of orographic maturity. At the north-eastern end of the Alps, especially

V. C. Browne, photo

Fig. 244. Rejuvenation in the valley of the Kawarau River, Otago, New Zealand.

in Styria, these mature surface features still exist. At other places they are dissected by very deep valleys. Thus, for example, in the southernmost parts of the Tyrol west of Lake Garda and south-east of Trient. Here the highlands have the soft rounded forms of a mature landscape. Those mountainous parts are separated from each other by valleys with very steep slopes. The slopes are evidently cut into the older formations. Even in the interior of the mountain chain we find remnants of its former maturity.[24]

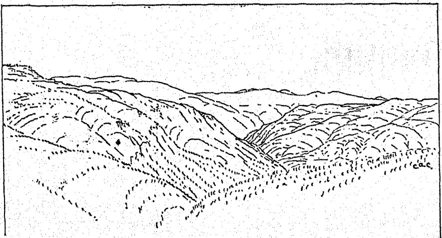


Fig. 245. Composite landscape forms, Franklin Valley, British Columbia, a late-mature upland surface dissected to a depth of 1000 feet by younger valleys of a later cycle.[13] (Drawn from a photograph.)

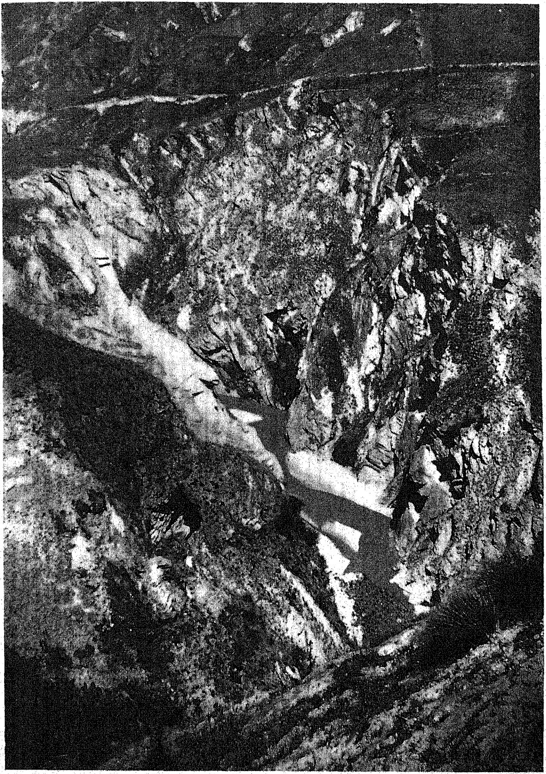


Fig. 246. Rapid rejuvenation has developed shoulders on the valley-side, Shotover River, New Zealand.

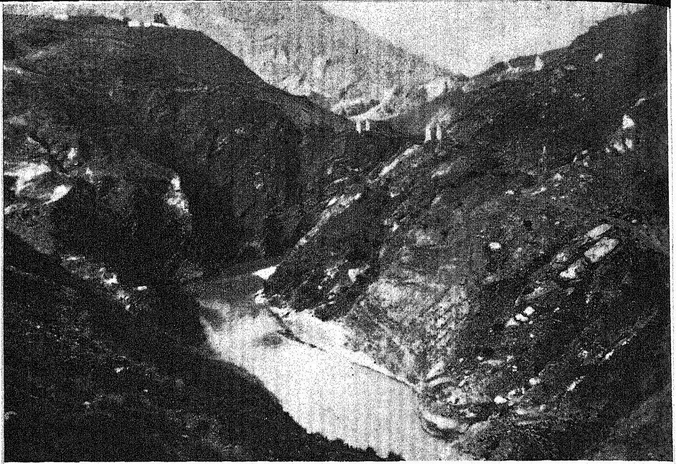


Fig. 247. Valley-in-valley form, with distinct shoulders, Shotover Valley, New Zealand.

According to W. Penck's method of explaining landscape forms (Chapter XIV) a valley-side shoulder does not indicate that uplift has taken place after an interval of still-stand (it being granted that upheaval and not some accident like climatic change has been the cause of valley incision); but it means rather that vertical corrasion and the upheaval that causes it have been *accelerated*—a quick change has taken place from very slowly accelerated upheaval to rapid uplift at perhaps a uniform rate. It is obvious that a shoulder may be thus developed; but its presence is not a sure indication of such a geological history.

Progressive Rejuvenation

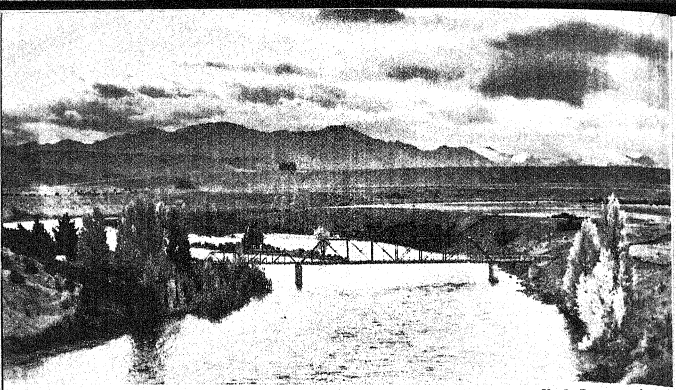
Interior parts of uniformly uplifted upland surfaces remain for a long time unaffected by the rejuvenation that follows some interrupting movements. Even in cases of slightly irregular and differential movement the slopes of upland surfaces distant from main rivers will be insufficiently altered in steepness by tilting to affect the rate of erosion on them immediately to any serious extent. Thus

rapid changes in the sculptured forms of the landscape do not necessarily follow immediately on uplift in inland localities unless movement of the surface has been distinctly differential; strong local warping produces immediate results, however, which will be described later in this chapter.

However long they may be delayed inland, landscape changes eventually follow any uplift, and forms related to (accordant with) the new base-level encroach, generally little by little, upon the landscape of the former cycle, first along the sides of the main rivers near their mouths, then farther inland, up the tributaries, and eventually up to the heads of all the branching headwater ravines. These results all follow, or accompany, regrading first of stream profiles and later of valley-side and valley-head slopes, for after any interrupting movement the grading processes degradation and aggradation come into operation, grading both streams and surfaces with respect to the new base-level.

The larger streams, graded and flowing down gentle declivities in the interrupted cycle, are indeed sensitive to changes of gradient throughout the affected region. Such parts of them as are steepened as a result of warping at once flow more rapidly and now have energy to spare beyond what is required to transport their as yet unaltered loads of waste. They degrade, therefore, reducing their declivities until a graded condition is again established. If, on the other hand, slight headward tilting has made a stream course too nearly level, the stream becomes too sluggish to carry its former load, and therefore deposits part of its load of waste in its valley (aggrades), thus building up and steepening its profile until it is again graded.

When a landscape is rejuvenated by interruption of a cycle, therefore, its valleys develop new features resulting from either degradation or aggradation, or, when warping has taken place, perhaps from both of these. The valley modifications may either be produced rapidly, but in this case sporadically throughout a landscape wherever warping has been sufficiently pronounced to affect the regimen of streams, or, in cases where positive or negative movement has been sensibly uniform throughout a region, may have to work their way slowly and systematically inland from river mouths. Locally, however, in river valleys, the effects are very similar in a general way whether produced immediately by tilting



V. C. Browne, photo

Fig. 248. Multicycle (or possibly fluvioglacial) terraces in the Upper Clutha Valley, New Zealand.

or making their appearance after long delay as a postponed consequence of a widespread movement of base-level. In the former case the varying depth to which new inner-valley trenches are cut, or the variable extent to which aggradation has taken place, together perhaps with angles at which regraded river profiles may be observed to intersect restored pre-interruption profiles, may give much information as to the extent, direction, and inclination of such tilting as has affected the landscape.

Though changes in slope due to warping are very rarely of sufficient steepness to affect hillsides appreciably, conspicuous regrading takes place in graded rivers when their down-valley gradients are altered even slightly, and this brings in its train important valley changes. Streams accelerated by down-valley tilting begin at once the development of valley-in-valley forms throughout the steepened parts of their courses. The transverse profiles of valleys thus rejuvenated exhibit in some parts of the river courses the simple valley-in-valley, in which an inner valley of youthful aspect broadens out above a more or less distinct shoulder at a varying height above the river to an open and mature form (Figs. 245-7). Commonly, however, parts of such valleys are bordered by valley-plain terraces (Fig. 244), and the shoulder of rejuvenation separating the forms of successive cycles is localised at the edge of a terrace. Multicycle valleys may exhibit several successive valley-plain terraces resembling those shown in Fig. 248.

Incised Meanders

Incised meanders (Fig. 249, *B*) may be developed from the curves of a meandering river course on the valley plain of a former cycle (Fig. 249, *A*), which either guide the headward erosion of a new-cycle inner trench or, where a valley has been steepened by tilting, are deepened more or less simultaneously throughout their length.[10] In many winding valleys the initial curvature has been thus inherited from meanders of a former cycle, though it may be that all other traces of the valley plain on which the meanders were formed have long ago been destroyed. It has been suggested, indeed,

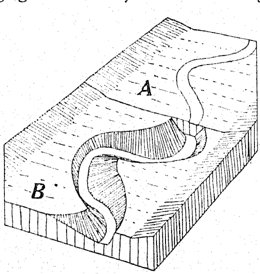


Fig. 249. Diagram illustrating the two-cycle theory of origin of incised (ingrown) meanders.
(From *Geomorphology*, also by the author.)

that this is the only way in which winding valleys with symmetrical curves—i.e. true incised meanders—around interlocking spurs are developed;[20] but some authors—e.g. Blache[3a] in his explanation of the origin of some very well developed and symmetrical meanders in the incised valleys of western Europe—reject the hypothesis of origin by incision of free meanders on an earlier-cycle flood plain even in the case of some for which such a theory of development has long been widely accepted as correct.

Symmetrically winding valleys with curves of large radius may be developed easily in soft-rock terrains, and where such incised meanders are found in a terrain of resistant rocks it is conceivable that they have been superposed from weak covering strata that have been removed by erosion.[28]

The controversy as to whether incised meanders are of two-cycle or single-cycle origin dates back to 1894, when Winslow[29] advocated the single-cycle theory in opposition to the opinion of Davis.[8] Mahard[22] has recently reaffirmed the obvious conclusion that both kinds of incised meanders exist. Details of the landscape form may prove the two-cycle explanation to be the correct one in certain cases (see Fig. 254) but are not to be relied on for this discrimination in many cases where the current cycle has reached an advanced stage.

Free swinging of meanders on a flood plain must obviously cease as soon as incision begins in a new cycle; but the momentum of the stream still carries it against the concave banks, which are liable to be undercut, and so some enlargement of curves almost inevitably takes place, and there is a tendency, as ever, to push the meanders also down-valley during their incision. The inner valley generally, therefore, assumes an asymmetrical transverse profile, with slip-off and undercut slopes, like that of any young valley that is increasing its curvature while vertical corrasion is in progress, though in plan the curves may be expected to be more symmetrical—"its new valley will be regularly curved, instead of irregularly crooked, as in its first youth".[9]

Intrenched and Ingrown Meanders

Incised meanders are of two kinds, *intrenched** and *ingrown,* the former exhibiting little or no contrast between the slopes on the inner and outer sides of curves (Fig. 250), and the latter having typical slip-off and undercut slopes (Figs. 249, 251). Meanders of the intrenched variety have been developed where, for some reason not obvious in all cases, no appreciable lateral corrasion has accompanied the incision of the meander, and where it may be safely inferred that there has been no appreciable increase in curvature or

* Rich,[25] who has also introduced the new term "ingrown", has thus limited the use of "intrenched", a term already in use by Davis and others as a synonym of "incised". Moore[23] has since proposed to discard "incised" as applied to meanders, replacing it as a generic, or "non-committal", term by "inclosed" (compare the French *encaissés*). It seems better, however, to retain the familiar "incised" in the generic sense. It was used by Davis in the non-committal way. "Intrenched", originally a synonym, can be used in the specialised, or specific, sense proposed by Rich. "Incised" and "ingrown" are not synonyms. Meanders that would now be described as "intrenched" were included by Davis in the generic category "incised". He did not suggest that these two terms should be used with contrasted meaning.

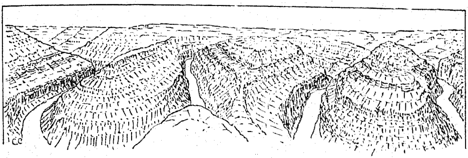
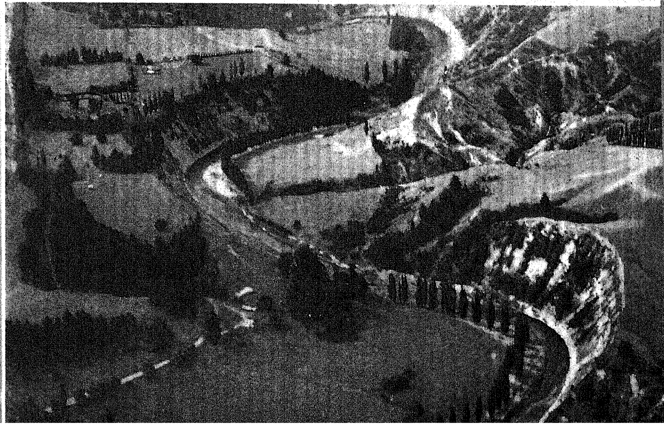


Fig. 250. Incised meanders of the intrenched variety, the "goose-necks" of the San Juan River, Utah. (From a photograph.)

down-valley sweep of the meanders (Fig. 250). Such intrenchment has been attributed to very rapid incision, notably to that which takes place just below the head of rejuvenation, the break of slope or nick in the river profile (Chapter XIX), that is found where an inner valley is developing headward in a direction guided always by the course of a pre-existing river after a regional uplift or lowering of the base-level has taken place.[15] According to this view the slower incision that results in forming ingrown meanders generally takes place when the rejuvenation that causes incision is

Fig. 251. Incised (ingrown) meanders in the Hawke's Bay district, New Zealand.
V. C. Browne, photo



due to a steepening of the river gradient by a tilting movement. Very slow incision, either going on as an accompaniment of slow uplift or tilting, or resulting perhaps from a hold-up of vertical corrasion due to the river's crossing a barrier of resistant rocks somewhere downstream, may encourage development of the extreme type of ingrown meanders, but rapid incision does not always produce the intrenched type. In the case of some New Zealand rivers very rapid incision has been accompanied by great enlargement of meanders (Fig. 251). Those of the Rangitikei (Fig. 158) are strongly ingrown, though incision of the inner valley has been rapid enough to leave tributaries hanging over it with discordant junctions (Fig.

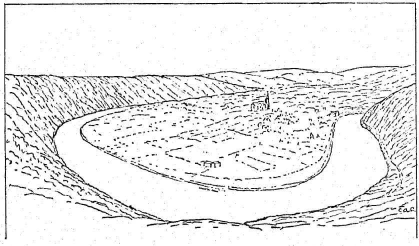


Fig. 252. Incised (ingrown) meander of the Meuse River, at Fumay, in northern France. (Drawn from a photograph.)

28), even where they are eroding only soft, scarcely consolidated material. Moore[23] finds an explanation of strictly vertical intrenchment in an underloaded condition of the eroding stream. "Downward corrasion is dominant in an underloaded stream, and underloading in general is favoured by steep gradients, large volume, and by resistant rocks in the floor of the valley" (MOORE).

First-cycle incised meanders must always be ingrown, but those inherited from free meanders may be ingrown also; it is only in special cases, indeed, that they are intrenched. Classical examples of large incised meanders that are strongly ingrown are Moccasin Bend, in the Tennessee River, near Chattanooga, and the bend of the Meuse at Fumay (Fig. 252).

The ingrown character of the meanders of an incised meandering valley is sometimes strikingly brought out by contrasting views from a high vantage point looking up and down the valley across its interlocking valley-side spurs. In the up-valley direction there may be revealed a succession of slip-off slopes occupied by ploughed and cultivated land, but the view down-valley will show only the steeper undercut slopes, perhaps forested, on the upstream sides of the spurs, "which give the valley an unoccupied appearance".[10]

Some West-European rivers with incised meanders have increased their curvature during the incision to the extent of cutting through the necks of spurs. Well-known examples of such cut-off spurs are

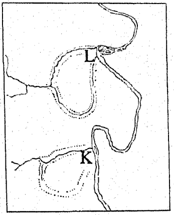
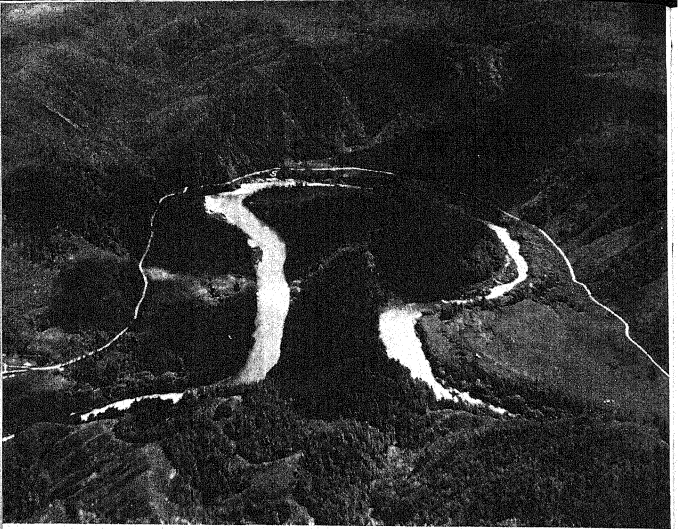


Fig. 253. Cut-off spurs in the valley of the Neckar at Lauffen (L) and Kirchheim (K).

those in the valley of the Moselle above Berncastel and in the Neckar Valley at Kirchheim and Lauffen (Fig. 253). A narrowed and nearly cut-off spur in the valley of the Buller River, New Zealand, shown in Fig. 254, has developed apparently during two-cycle incision, for there is a distinct shoulder of rejuvenation very high up on the valley side.

Effects of Land Warping

Warping has reversed the flow of parts of some rivers. Terraces bordering the river valley may be found to slope upstream, or the pattern of tributary junctions may be "barbed", or, as Taylor[27] has termed them in Australia, "boathook bends". (See, for example, the barbed junctions of tributaries with the African rivers Kafu and



V. C. Browne, photo

Fig. 254. Incised (ingrown) meanders and narrowed spur in the valley of the Buller River, New Zealand. View looking north. At *S* the White Creek fault crosses the river (see Chapter XXI). There is a shoulder of rejuvenation high up on the valley side.

Katonga, shown in Fig. 38.) It cannot be assumed, however, that all barbed junctions indicate reversal, or that every reversal is due to warping or tilting.[4] Some reversal of headwater streams takes place when divides migrate as a result of slow erosional processes; and some barbed junctions result from headward erosion at places where weak zones (perhaps fault zones) intersect the structural grain of a terrain of inclined strata obliquely, or from diversion of rivers along fault angles across land surfaces on which adjustment to structure is already developed (p. 382).

Headward tilting that is insufficient to cause reversal may result in profound aggradational changes in river valleys. These will be effective where even a minute reduction in steepness of gradient is felt by a large river throughout a great part of its length.

Effect of Strong Tilting on Small Streams

Small streams that are too steep to be reversed may be affected by aggradation. Instances of recent tilting of the surface that have been of sufficient steepness to affect conspicuously the valleys of small and steep-grade streams are found only in parts of the seismic belts—for example, in certain districts of California and New Zealand. Along the down-warped eastern side of the Port Nicholson

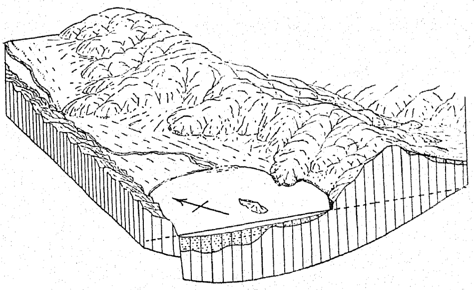


Fig. 255. Generalised diagram of part of the tectonic depression, or basin, that has formed the Hutt Valley and Port Nicholson, or Wellington Harbour, New Zealand. At the right (south-east) is the Wainui-o-mata valley.

and Hutt Valley depression (the Wellington Harbour area) in New Zealand (Fig. 255) recent westward tilting of about 175 feet per mile has affected an early-mature land surface of rather strong relief.[6] This is part of the basin-making warping that has produced the depression as a whole, a warping of which there is abundant evidence (Fig. 256). Main streams flow so nearly parallel to the hinge-line of the tilt that they are not much affected, but grouped tributaries near the headwaters of two of these enter them from the west, and the valleys of the tributaries have been filled to the heads with swampy-surfaced alluvium to the extent of partly burying spurs and converting them into islands (Fig. 257) and peninsulas (Fig. 258).

V. C. Browne, photo

Fig. 256. Strongly tilted and warped land surface forming the west side of the tectonic basin of Port Nicholson, New Zealand (compare Fig. 255). The coastal forms at the left indicate uplift, though the coast since it rose has been attacked by marine erosion, and at the right depression, with drowning of the landforms. Port Nicholson (Wellington Harbour) is seen in the distance.

Effect of Sideward Tilting on a River Valley

Large graded rivers are very sensitive to land warping, provided this takes place in the lengthwise direction and extends far enough to call for a regrading of the river course either by renewed down-cutting or by infilling of its channel to an appreciable depth. If, on the other hand, the course of a river is strictly parallel to a hinge-line of warping, even a strong tilt will fail to produce an effect. Warping or tilting of the land is a slow process (except in some cases in the vicinity of active faults) and it is inconceivable that it will shift a river any appreciable distance laterally. The old-fashioned idea of a distinct and recognisable effect due to the deflecting force of the earth's rotation, feeble though this must be in its tendency to shift rivers laterally as compared with the systematic sweeping of meanders

and the perhaps fortuitous swinging of meander belts, is based on the existence of a definitely calculable force;[14, 17, 19] but the tendency towards deflection produced by a minute tilt towards one side of a valley is incalculable. It must be negligible,[7] though some geologists have thought otherwise. Gheyselinck[16] states that when anticlinal crests are formed "the rivers are shifted sideways along the upfolded strata [surface?]. And, conversely, such valley displacements assist

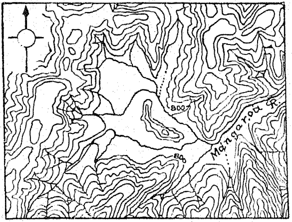


Fig. 257. Backward tilted, deeply aggraded headwater streams affected by westward downwarping towards the Hutt Valley tectonic basin, New Zealand. The photograph is a view north-westward across the central part of the area mapped. Contour interval, 100 feet.

(From *Geomorphology,* also by the author.)

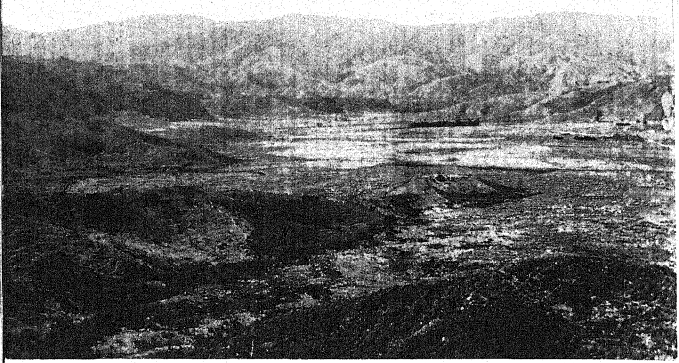


Fig. 258. Headwater tributaries of the Wainui-o-mata River, New Zealand, aggraded as a result of strong headward tilting so as to make extensive swampy flats. View looking south-east from the valley-head divide.

in the search for geological structure suggestive of petroleum". This sounds helpful, but the reader is not informed how the geologist is to recognise that lateral displacement of rivers resulting from local surface tilting has taken place, and the author has apparently failed to realise that this problem is quite distinct from that presented by simple cases of homoclinal shifting. Hanson-Lowe[18] has ventured the more cautious statement that "rivers flowing parallel to the hinge [of surface tilting] would probably show a tendency to lateral displacement", but has not discussed the mechanism of the process.

It might be suggested that lateral shifting would cause a river to undercut and steepen bluffs along that side of its valley towards which it has (supposedly) been forced over, making the form of the valley asymmetrical, and it is worth while to examine this proposition deductively.[7] One may assume to begin with that before lateral tilting takes place the river is flowing in a mature valley with a flood plain. There is no difficulty in postulating conditions under which very gradual tilting will fail to cause a river that flows on the floor of such a valley in a well-defined channel to change its course at all, at any rate if the general effect of the accompanying earth movement is to bring about some degradation in the valley. This is the familiar case of vertical incision of the kind that results

in superposition of rivers. Rapid tilting, on the other hand, or a cumulative succession of intermittent small movements each of which is instantaneous (or at least very rapid) will generally cause a river to take a new course along what is henceforth the low side of its former flood plain, which is now transversely tilted.

There is no reason why the river, as it re-shapes its valley after this event, should undercut more vigorously on one side than on

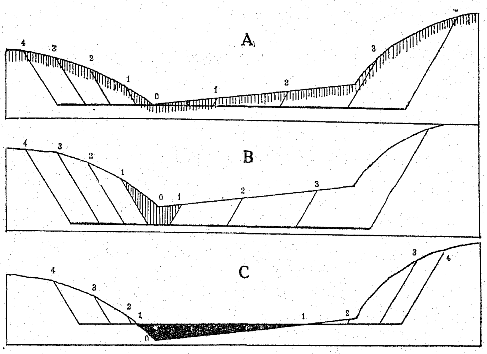


Fig. 259. A: Initial and sequential cross profiles after transverse tilting of a valley. O, initial position of the stream; 11, 22, 33, 44, successive profiles developed by lateral corrasion.
B: Initial, O, and sequential profiles, of which 11 is developed in a phase of vertical corrasion, and 22, 33, and 44 are the results of lateral corrasion at later stages.
C: Initial, O, and sequential profiles, of which the profile 11 is developed in an aggradational phase.

the other, but owing to asymmetry of the cross profile after tilting (Fig. 259, A) a profile with higher bluffs on the side that has been depressed may be expected to appear in the early youth of the post-tilting epicycle. This will be so because the now transversely tilted floor of the pre-existing valley will still be in evidence; and early stages of post-tilting valley development will be characterised by the presence along one side of the valley of a sloping terrace, the

surface of which is the now transversely tilted floor of the former valley. The terrace-edge will be bordered at first only by a line of low undercut bluffs contrasting with the higher bluffs on the opposite (depressed) side of the valley (Fig. 259, A: 11); but the bluffs that now form the front of the terrace will become higher as the new valley is widened by lateral stream corrasion (stage 22). When the sloping terrace which is a remnant of the former valley floor has been destroyed by this process (33, 44), the valley will assume a typical mature cross profile, and the bluffs will then probably be higher on the upheaved than on the depressed side because of the uplift of the whole land surface in that direction.

In the deduction of the foregoing hypothesis no appreciable change of gradient or load in the river has been allowed for. It is more than probable, however, that immediately after the occurrence of the tilting movement the river will aggrade or degrade its course. If the latter is the case, a stage of valley-in-valley rejuvenation will be followed (after grade is attained) by stages similar to those already outlined (Fig. 259, B). If, on the other hand, an aggradational phase is passed through, and is followed by stages of lateral cutting at constant level after the valley has become graded, the successive profiles will be of the general nature of those numbered 11-44 in Fig. 259, C. As the diagrams suggest, the valley will be bordered in most cases by bluffs, and these will probably be of greater height on the upheaved than on the depressed side.

Though effects such as those deduced above may be looked for in the valleys of rivers flowing along strips of very strongly tilted country, no positive examples seem to have been observed and recorded. Evidence of change of form as a result of tilting of this kind might be sought in the valley of the Wainui-o-mata River, referred to already in this chapter, which flows along the tilted land surface shown in Fig. 255, right. Beyond a certain amount of aggradation in some reaches, however, the valley of this river yields no positive evidence of re-shaping as a result of the transverse surface tilt. The explanation of this is satisfactorily found in the fact that the valley is now fully mature in the post-tilting epicycle. So, as may be expected when this stage is reached, the tilted floor of a former valley characteristic of a hypothetical initial or infantile stage from which this mature sequential valley has been shaped by erosion has been destroyed, and no traces of the initial form survive. Thus the

landscape forms of the main Wainui-o-mata valley (as distinguished from its westward-branching headwater tributaries described on p. 333) afford at the present day no positive evidence regarding the tilt of which other features in the vicinity offer proof.

Aggradation of Intermont Basins Produced by Warping

Warping (or deformation by faulting) on a hinge-line transverse to a river may cause headward tilting, even to the extent of reversal of slope, of a part of its course (Fig. 260). This may be the result of

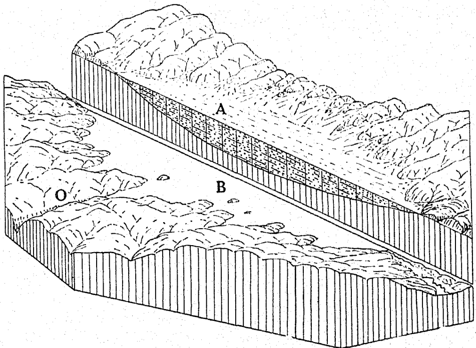


Fig. 260. Results of warping affecting the profile of a river valley. A, aggradation, with formation of a basin plain, has gone on *pari passu* with warping; B, rapid warping has resulted in the ponding of a lake in the warped valley, with embayments in the valleys of drowned tributaries; O, possible new outlet. The direction of (former) river flow is from left to right.

upwarping or upfaulting of a belt of country crossed by the river and through which it may be able to maintain its course as an antecedent. Commonly aggradation proceeds during the continuance of the deformation, and a basin plain is built by the river in an inland or intermont basin while farther downstream it is cutting an antecedent gorge (Fig. 260, A). Reversal of slope of the former valley floor takes place in this case only after it has been buried, and the river maintains for itself a constant slope in the direction

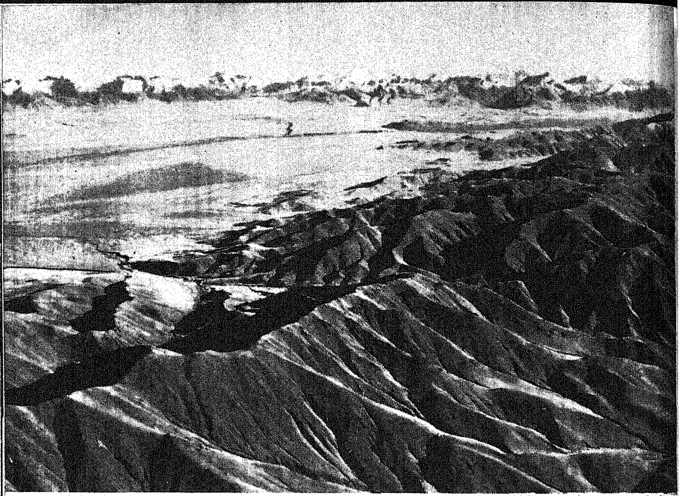
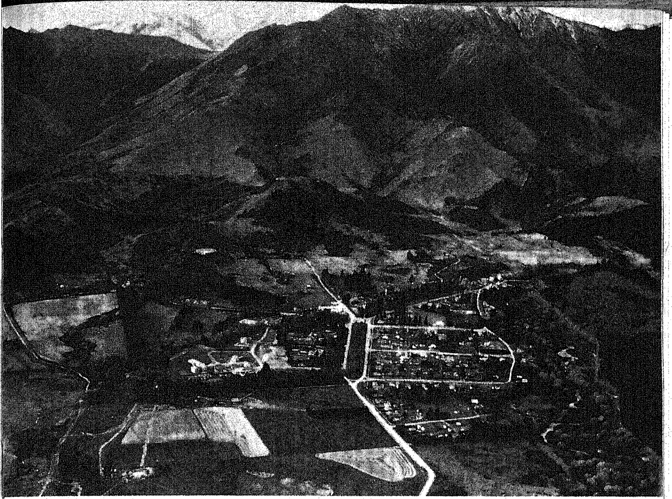


Photo from N.Z. Aerial Mapping Ltd.

Fig. 261. The Mackenzie basin plain, New Zealand, which has been formed by aggradation in a downwarped and faulted depression (compare Fig. 260). It is traversed by the Waitaki River, which leaves it by way of a gorge (Fig. 284) through an upwarped and faulted belt, of which the Two Thumb Range (foreground) is part.

in which it continues to flow by building a bridge of alluvial deposits across the tectonic basin as it is formed (Fig. 261).

Should the earth movements that result in the formation of the basin go on sufficiently rapidly, however, ponding of the river, with formation of a lake in the basin, must take place. Though examples are rare of lakes ponded in river valleys by simple transverse warping[8] such as is illustrated in the diagram (Fig. 260, B; compare Fig. 38), many lie in more complex tectonic basins (Chapter V). A lake formed by the ponding of a vigorous river can have but a short life, as it will be rapidly filled by the growth of deltas or drained by erosional lowering of the level of the outlet. The out-flowing stream may continue to follow the line of the former river as an antecedent, but if there is a low enough gap in the surrounding hills, the lake will overflow through it (as at O, in Fig. 260, B), the river being thus diverted by ponding as a result of warping (or



V. C. Browne, photo

Fig. 262. The embayed margin of a basin plain, Hanmer Plain, New Zealand.

deformation by faulting). As regards the abandonment of the former course, this is a case of defeat, and the river in the former valley has been *beheaded by warping*. The new course taken by the river overflowing from the lake will almost certainly fail to fit the river, which must proceed at once to adapt and grade it for itself. The river will be a misfit of the "overfit" variety, and grading of its course will lower the outlet of the lake and will eventually, and perhaps rapidly, drain it, unless its floor has been warped down below the local base-level.

Basin plains resulting from aggradation over a land surface of considerable relief where a cycle has been interrupted by deformation of the surface will have irregular, embayed outlines very like those of lakes that have been similarly formed, for the component fans of many streams will extend up their valleys (Fig. 262). After thick alluviation has taken place in a downwarped basin, indeed, fan-filled embayments of the upland, or extensions of the plain, may occupy even valleys opened up or enlarged by erosion during the progress

of the deformation. Where a basin has some fault boundaries, however, these are little altered by aggradation, and that little only when movement on the faults has ceased. Peninsulas and islands, either of a pre-existing relief or due to irregularity of deformation, may be partly or wholly buried beneath the accumulating alluvium, but, whatever their origin, they are subject to erosion until they are buried, and so they always underlie the basin-plain deposits unconformably.

Campbell's Law of Migration of Divides

When a land surface with some relief is affected by warping, though diversion of streams by ponding and alluviation may occur, an immediate general transfer of divides to the axes of upwarping is obviously prevented by the fact that rivers are imprisoned in pre-existing valleys; and yet divides will immediately begin to migrate towards these axes, and main divides must eventually come to coincide with them fairly closely.[5] The explanation of such migration, according to "Campbell's law", is simple enough. Where two streams that head opposite to each other are affected by an even lengthwise tilting movement, that one whose declivity is increased cuts down vigorously and grows in length headward at the expense of the other. If the tilting that affects them is part of a general warping, the divide migrates towards an axis of upwarping. The general law that axes of upwarping become divides is subject to exception where such axes are crossed by antecedent rivers.

Migration of divides according to Campbell's law may result in a lateral migration of a valley system as a whole (as distinguished from the individual valley of the main river). Thus, though it is probably not true of individual rivers (p. 334), it is true of valley systems that they migrate laterally down the dip of a tilted surface, so that they may come eventually to coincide in position with axes of downwarping. The transfer of drainage to new lines in or near axes of downwarping will be a very slow process, however, and will be delayed until it can be effected by a succession of stream captures that are stimulated by the tilt.[7]

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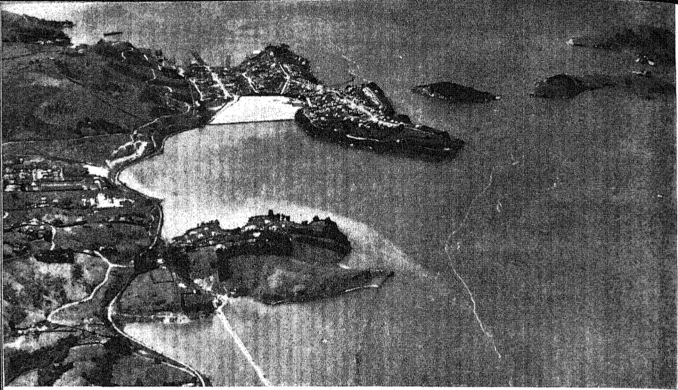
CHAPTER XIX

Positive and Negative Movements of Base-level

THAT CASE OF COMPOSITE-LANDSCAPE DEVELOPMENT MAY BE NOW examined in which either the level of the ocean rises or sinks or earth movement takes place that is not deformational but regional, or "epeirogenic", i.e. simple depression or upheaval without any accompanying warping or differential movement of any kind. Even though, as Davis[13] believed, such movement of the land, when it takes place, is merely a special case and perhaps a rare event as compared with a more general case of diversified uplift, there are regions in which warping and tilting movements, if they have occurred at all, have been inappreciable at the initiation of erosion in the latest or in recent cycles. Regions in which there has been a close approximation to epeirogenic movement simulate in their reaction to revived erosion the effects of eustatic change of level. Thus it is not known whether earth movements or changes of ocean level are mainly responsible for interruptions of the geomorphic cycle in stable regions.

POSITIVE MOVEMENT OR PARTIAL SUBMERGENCE

The simple case of eustatic rise of sea-level or regional subsidence of the land produces immediate effects on the landscape only where it results in partial submergence, with creation of a new shoreline, "drowning" valleys, "betrunking" rivers, "dismembering" river systems, forming estuaries, harbours, rias, and the innumerable bays and minor indentations that diversify a majority of the coasts of the world (Fig. 263). These are shoreline features and their further development is not discussed in this book. Over that part of the land that escapes submergence there may be a slight slowing down of the general wastage of the land surface, but this seems incapable of demonstration, as it produces no appreciable changes in the relief. According to the ruling of Davis,[13] a new cycle has been inaugurated, however, and changes, at least in the valleys of the landscape, will follow in due course. Rivers, large and small, build out



V. C. Browne, photo

Fig. 263. "Drowning" of valleys by partial submergence of the land, at Port Chalmers, New Zealand. A former divide is here submerged.

deltas in the still waters of bay heads and estuaries into which they now flow, and the streams that have been betrunked and shortened by submergence thus grow in length again seaward. As delta-building streams, if previously graded, must aggrade inland (Chapter XV) in order to continue flowing and maintain grade, it follows that valleys in regions of subsidence and submergence become somewhat aggraded. Clearly such aggradation can go on only progressively with the outgrowth of bay-head (or lake-head) deltas. Its effects are seen in Figs. 207 and 211. As there are various other possible causes of aggradation, such as have been mentioned in earlier chapters, aggraded valleys cannot of themselves be accepted as proof of a positive movement of the general base-level (subsidence or submergence).

It has been pointed out by Baulig[5] that the abundance of aggraded valleys in which alluviation has been due solely to a movement of base-level has led to an erroneous belief that aggradation in the lower courses ("plains tracts" as they have been vaguely termed) of rivers is a normal feature of mature valleys. This error based on a false induction is firmly embedded in elementary text-book geomorphology.

Emergence, or Negative Movement

Near the margin of the sea it is obvious that even the smallest streams have felt the effects of the most recent upheaval of the land, if such has been the latest event, for they have begun to rejuvenate their valleys (Fig. 256, left), or, if the land is now fringed by a coastal plain, all the streams are engaged in cutting first-cycle valleys, which soon become sharply incised in the surface of the plain, so that the rivers are then ready to commence the rejuvenation of the hinterland.

Rejuvenation due to Cliff Recession

Besides emergence there are other possible causes of rejuvenation, some of which have been referred to already in a discussion of the causes of river terracing (Chapter XIII). By far the commonest cause of rejuvenation of streams at their mouths is a rapid recession of the shoreline under the attack of storm waves. Along the majority of coasts the most recent change in the relation of sea and land has been a submergence caused by eustatic rise of sea-level, and, where other lines of reasoning lead to the conclusion that this has taken place, it is generally found that cliff recession, or marine retrogradation, has been the sole cause of strong rejuvenation that is commonly developed in the lower valleys of small streams entering the sea. Along the wave-beaten coast of Cornwall and Devon, for example, it has been noted that ravine mouths hang (at various heights according to the gradients of the streams) above the sea.[14a, 26] The larger streams in such sea-cliff hanging valleys have succeeded in cutting young inner trenches, or at least have notched the lips that overhang the sea. In some terrains of soft rocks, such as the chalk that forms the shores of the Strait of Dover (Fig. 264), cliff recession is so far advanced that streams are not only betrunked and thus left issuing from hanging valleys (French, *valleuses*)[27] but are even also dismembered, so that streams that were originally tributaries now enter the sea by separate mouths.[27]

As the shoreline does not as a rule retreat at the mouths of the larger rivers, because of the abundance of waste brought down to the sea by the rivers, the effects of rejuvenation due to cliff recession are rarely seen far inland.

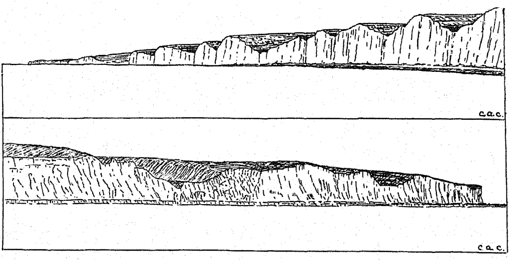


Fig. 264. Betrunked and incipiently rejuvenated valleys (*valleuses*) on the French (above) and English shores (below) of the Strait of Dover. (Drawn from photographs.)

(From *Geomorphology,* also by the author.)

Revival of Erosion

No immediate changes in the inland relief of an uplifted or emergent surface are produced by the uplift or emergence itself, for relief changes that result from rejuvenation are of a sequential kind that require time for their development. This is the case in which denudation inland proceeds unchangingly, as though the interrupted cycle were still current, "until news of the upheaval is brought . . . by the retrogressive erosion of peripheral streams" (Davis).[13] The region affected lies at the rear of a newly emerged coastal plain, and after its rivers, where they are extended across this strip, have deepened their valleys as far as the fall zone (Fig. 66, p. 92) they begin the redissection of the hinterland. Though graded farther upstream, the rivers have steepened profiles at the fall zone, and each stream in the oversteep part of its course has again the velocity and energy of youth. Erosion is *revived,* and the stream, itself rejuvenated, proceeds to rejuvenate its valley by taking up again the task of vertical corrasion. The falls and rapids that have made their appearance where old rocks are first exposed at the fall zone work their way upstream and inland from this point as the head of a new and young valley guided in its headward erosion by the line the stream is already following—that is to say, the new valley is within that of the former cycle as "valley-in-valley". As

there is a ready-made stream in each valley, which is well supplied with water, erosion is as rapid as the strength of the rocks will allow, and below the headwardly progressing zone of falls and rapids the inner valley eventually becomes graded with respect to the new base-level (Fig. 265). Deepening of the valley of the main river lowers local base-levels as it progresses inland; valley-in-valley development (rejuvenation) begins in tributaries as soon as each of these feels the effect of lowered base-level; and eventually rejuvenation gnaws gradually into the upland.

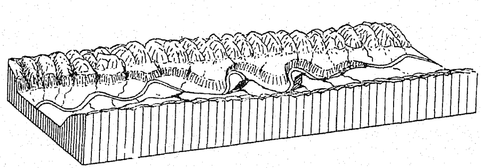


Fig. 265. Rejuvenation of a river and its valley proceeding by headward erosion.

Multicycle Valleys

Rejuvenation may recur at intervals, and a succession of valleys of revived erosion may be found progressing headward one within the other (Fig. 266). As an example of a valley comprising such multicycle forms that of the Snowy River, of Australia, may be cited.

> This stream has a course of 300 miles, approximately, from its source in the high fault block of Kosciusko to the Gippsland Lakes, in Victoria. . . . Its descent from the subsummit upland . . . is by means of a series of relatively youthful valleys opening out into each other, the lower being embraced within the higher and outer forms, and the valleys descending to each other by means of rapids and gorges. The rock structures within which these "valley-in-valley" forms occur are more or less homogeneous in that they occur in the main within a massive gneissic granitoid rock. (Andrews).[1]

In the old-rock mountain massifs of Europe Baulig[8] describes how every valley "is composed really of elementary valleys [valley elements] successively younger, stepping down one to another in

longitudinal profile, and inset one within another in transverse profile . . . Each valley element is . . . more maturely developed downstream than upstream". He notes, moreover, that a similar pattern of inset and down-stepping valley elements is to be found also in European localities far from mountains and has been clearly recognised in many regions of quite moderate relief. On weak-rock terrains the interfluves separating the widened mature lower valleys both of main rivers and large tributaries have become local peneplains, and those of successive cycles have been reduced to benches (arranged as a flight of steps).

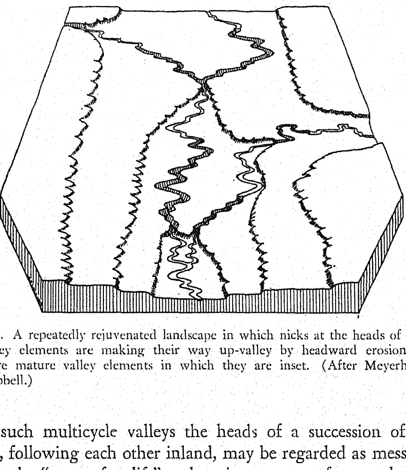


Fig. 266. A repeatedly rejuvenated landscape in which nicks at the heads of younger valley elements are making their way up-valley by headward erosion within more mature valley elements in which they are inset. (After Meyerhoff and Hubbell.)

In such multicycle valleys the heads of a succession of inner valleys, following each other inland, may be regarded as messengers bearing the "news of uplift" and setting out one after another after successive uplifts have occurred. In weak rocks, such as the deeply dissected marine mudstones of late Tertiary age in the Wanganui district in New Zealand, the inner valleys even of small streams have rapidly become mature and open in the manner shown in Fig. 265. Such a mature valley followed upstream soon narrows, displays

youthful features, and steepens, and is discovered to be gnawing headward into the floor of the open, mature valley of the penultimate cycle; but this again may, a few miles farther on, be found to be rejuvenating in a similar way an open valley of an antepenultimate cycle just now receiving news of the last uplift but one, and so on to cycles still farther back from the present.

Relics of areas eroded to late maturity or reduced locally to peneplains, portions really of the floors of widely opened late-mature valleys and subsequent lowlands of an earlier time, remain above the inner and younger valleys of some rejuvenated rivers as benches. Such benches as a whole have been termed "berms" by Campbell, Bascom,[4] and Cole,[12] and have been called also "strath terraces".* They are not as a rule simply terraces, i.e. river terraces, for they commonly include not only parts of flood plains but also of valley sides and lowlands (commonly subsequent) developed as local or partial peneplains, or "straths", as Bucher[11a] prefers to call them.

Among the most important minor features diagnostic of intermediate cycles are wind gaps in the crests of subsequent ridges.[3, 23] These are younger than the oldest peneplains that survive on the even crestlines of hard-rock ridges but are relics of valleys that are very ancient as compared with those in which rivers are now flowing and eroding. Some wind gaps are composite in profile and thus preserve forms of more than one ancient cycle, being "hung up, so to speak, out of reach of . . . erosion."[22]

The Head of Rejuvenation in a River Profile

Accurately plotted profiles of many European and North American rivers in their upper courses, and of innumerable tributary streams, show them to be graded only in parts.[6] The profiles as a whole are by no means smooth, and afford proofs of multicycle erosion, for successive nearly level, graded parts are joined by ungraded steeper parts stepping up to the next higher graded reaches by convex "nicks"† (German, *Knick*)[31] in the profiles.

* O. D. von Engeln discusses these terms (*Geomorphology*, 1942, pp. 221-224).

† "Knickpoint", introduced by E. B. Knopf,[22] is widely used instead of "nick". "Knickpoint, derived from the German *Knickpunkt*, is used by chemists to denote an abrupt change in direction from a gentle concave curve to a curve that is convex upward" (Knopf).

In the lower reaches of the stream . . . there will be a development of a new concave curve of maturity, and, inasmuch as erosion works progressively backward, the reduction of the former stream profile to a new curve will progress backward from mouth to source. Obviously at the headward limit of this reduction to a new grade there will be an arch in the curve—a change in the stream profile from a concave to a convex curve. . . . A stream . . . can show . . . a succession of bends or knickpoints in the curve. (KNOPF and JONAS).[23]

It is true, of course, that somewhat similar river profiles may be developed in the course of a single cycle of erosion, when they are due to the presence of barriers of resistant rock holding up rivers in young, ungraded gorges, which separate graded reaches across weaker rock outcrops; but nicks in a river profile and alternation of mature and open with narrow and young stretches of valley may be independent of structure, occurring where the rocks are homogeneous as far as their resistance to erosion is concerned. Even where nicks occur at resistant outcrops, this is quite commonly a result merely of retardation at such points of headward erosion due to rejuvenation,[19] and the most widely accepted explanation of nicks in valley profiles is that they are for the most part the effects of successive lowerings of base-level. Regional correlation of such features, which has been carried out in France, has brought out such convincing evidence of uniform lowerings of base-level throughout a succession of cycles that Baulig[7, 8] confidently regards these as the results of successive rapid changes of the ocean level without any complications due to crustal movements. Successive river profiles developed in the intervals between successive downward movements of base-level in the land mass are, when restored by extrapolation, divergent downstream, the arrangement termed "concordant" by Briquet (p. 210), as would be expected from theoretical considerations.

One implication of the hypothesis of uniformly (eustatically) sinking base-level is that cycles must remain current inland long after they have been interrupted near the sea coast. They are, as it were, waves of erosion successively propagated inland, and the only logical method of indicating that landforms belong to any particular cycle is, according to Briquet,[11] to date each cycle geologically according to the date of the base-level that originated each impulse or cycle.

though, as pointed out by Baulig,[6] this leads to the peculiar result that a Pleistocene deposit (a glacial moraine) may be dissected by erosion attributable to a Pliocene cycle. Notwithstanding this anomaly, however, Baulig[8] is unable to accept the suggestion of Davis[13] that a new cycle should be declared inaugurated throughout a region immediately a change of base-level has taken place (p. 283).

Multicycle Landscapes

A classic example of a landscape in which forms developed in three very distinct geomorphic cycles are recognised is that of Scotland, according to the interpretation of Peach and Horne (Chapter XVI). Another is that of the Limousin, in the north-western part of the Central Plateau of France, which has been described in detail by Demangeon.[14] Here a highland peneplain at an altitude of about 3000 feet is undergoing dissection. In a second cycle erosion has developed a widespread peneplain now forming uplands of low relief at altitudes of 1000 to 1500 feet, though "where the higher reliefs are grouped in the still preserved highlands of the first cycle the work of the second is seen only in broad valley-heads that appear as open embayments in the highland border". Third-cycle valleys have their heads in "narrow, young gorges which rapidly deepen beneath the upland valley floors, and become well graded and maturely open valleys"* downstream, especially on a terrain of relatively weak rocks bordering the harder rocks of the highlands and upland.

Wherever rivers with nicked and stepped profiles dissect a land mass traces of benched profiles also are to be found on the highland and upland flanks of the mountains, though in some cases the only indications of these that have escaped destruction by erosion are to be seen in some measure of summit-level accordance (Fig. 267). Their existence has been inferred from studies of topographic maps, in some of which a method of "projected profiles" has been employed. As stated by Barrell,[3] its originator, "belts of country are selected which stand up highest. That line of sight is taken across this belt which is at right angles to the general slope of the topography and gives, therefore, the least concealment of the background by the foreground. It is the direction of sight which is best

* Quotations from a review by W. M. Davis.

adapted to show the character of the culminating upland surface, as to whether it was a plane or a series of planes." With slight modifications this procedure has been employed by various investigators who have adopted the projected-profile method of research (Fig. 268); but in addition to that based on projected profiles other

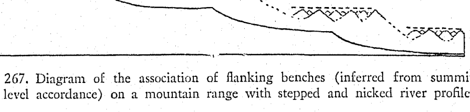


Fig. 267. Diagram of the association of flanking benches (inferred from summit-level accordance) on a mountain range with stepped and nicked river profiles.

methods of statistical treatment of the data available on topographic maps have also been devised[6, 17, 26, 28, 36, 38] and applied with a considerable measure of success to the treatment of the problem of restoration of ancient land surfaces now dissected.

Profile studies have indicated that numerous benches break the continuity of a surface formerly thought to be a single continuous peneplain (the "Schooley peneplain") in eastern North America. Barrell favoured the hypothesis that these benches were, at least finally, shaped by marine erosion, marking successively lower traces of the sea margin. He believed there were present in the area he studied, besides higher benches, eight that were developed in

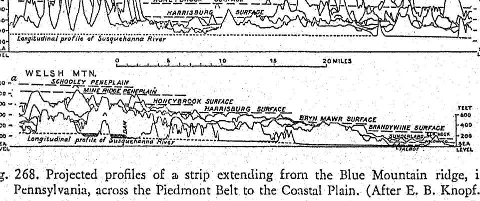


Fig. 268. Projected profiles of a strip extending from the Blue Mountain ridge, in Pennsylvania, across the Piedmont Belt to the Coastal Plain. (After E. B. Knopf.)

Pliocene and Pleistocene times. The study of projected profiles has yielded evidence also of accordance of summit levels on dissected strath terraces bordering inner valleys in the Northern Appalachians sufficient, it is held, to indicate the former existence of high-level wide valleys, and to establish a succession of cycles in the development of the valleys as they exist to-day. Restoration of the composite valley-side slopes indicates their development in a "quickening series of uplifts".[3]

Studies made in the southern Appalachians[4, 12, 23] and in the Connecticut Valley by other workers have confirmed the conclusions of Barrell in a general way for eastern North America, but normal valley-development with peneplanation, rather than marine erosion, seems to have been the process dominant in the cutting of benches, of which from four[12] to ten[23] have been recognised in the former region and fourteen in the latter.[29] The benches are said to "reflect regional [uniform] uplifts and represent the degradational forms which developed during the cycles of quiescence that followed the uplift".[29]

With the exception of Stose,[37] who has maintained a theory of faulting and marginal down-warping of very ancient surfaces in the southern Appalachians, the later workers in eastern North America have come to regard even the oldest of the summit-level surfaces as of comparatively modern origin. They intersect the more ancient Fall Zone peneplain (p. 313), which is a resurrected Cretaceous surface. It is impossible, indeed, to account for the vast bulk of sediments under the coastal plain and continental shelf of eastern North America without postulating upheaval and deep and extensive denudation of the Appalachian region in post-Cretaceous time.[2]

Many-stepped multicycle landscapes have been recognised in Europe also. Near Lake Lugano, for example, just outside the glaciated region, as interpreted by one investigator,

the Colla valley is a stream-eroded valley with a stepped longitudinal profile. Repeated uplifts of the mountains have initiated new systems of downcutting (cycles according to the terminology of Davis), each of which migrated up-valley. Distinct remnants of no less than fifteen such cycles can be recognised, each characterised in longitudinal profile by a stretch of gentle gradient followed up-stream by a steeper gradient, and in cross-profile by valley walls of definite slope. (Jaeger).[18]

Problems of correlation[35a] may introduce doubt as to the number of cycles actually represented by surviving landscape forms, and the present-day altitudes assigned to the base-levels at which ancient valleys were developed are generally questionable, for reasons which Miller[30] has shown to be unavoidable. Nevertheless, "this simple and apparently legitimate extension of the cycle theory has been long accepted in France . . . It underlies the many studies devoted to step-like erosion surfaces (*niveaux d'erosion étagés*)".[8]

Statistical study of topographic data has convinced Hollingworth[17] of the existence of at least three, and probably more, step-like benches fringing Britain. (Some, but not all, parts of these are marine wave-cut terraces rather than peneplains.)[26] Peneplains of successive ages with similar arrangement have been described in many regions. Commonly, however, only a limited number of steps are known, or have been described. In Central and South Africa, for example, steps of a broad staircase have been assigned dates from Jurassic onward.[15] Of these that ascribed confidently to the Miocene,[40] or rather to a vast erosion period ending some time in the Miocene, is by far the most extensively preserved. In South Africa "this surface is recognisable almost everywhere . . . and almost everywhere it is the same, an illimitable expanse of dead-flat country."[21] Marginally, however, this "Miocene" surface is replaced by an "end-Tertiary" peneplain (Fig. 213A), which in its turn is suffering dissection.

As a result of statistical analysis of map data the vast "peneplain" testifying to erosion throughout a vast period that forms most of the surface of eastern Australia, though known to be warped and broken in places by faults, has been found to be in all probability also a composite erosion surface comprising steps developed in successive cycles. Maze[28] claims to recognise at altitudes from 2200 to 4000 feet in the Orange district of New South Wales extensive remnants of peneplains developed in several distinct cycles.

In the Andes of Peru summit areas are for the most part a peneplain. Extensive remnants of this are the cold pasture lands, called "punas", at altitudes of from thirteen to fifteen thousand feet.[26a] Uplifted 10,000 feet,[16] though not quite uniformly, this highland surface is dissected by valleys in which there is evidence of rejuvenation at successive stages of upheaval.[26a]

Two peneplains,[24] and even a stair-like succession of surfaces,[34, 30] have been described in the Rocky Mountain region, but the evidence that these are peneplains has been criticised by Rich,[33] who favours an alternative hypothesis to explain the observed facts. According to this the "multiple erosion surfaces" have resulted from erosion of benches at successively *higher* levels, the surfaces being progressively buried and subsequently resurrected.[34]

Ideally, multicycle benching, if correctly interpreted as due to the development of peneplains at successively lower levels, would be produced by intermittent uniform uplift (or eustatic emergence) but some very gentle tilting and broad doming might accompany such upheaval. If tilting be only marginal to the upheaved area the effect inland will eventually be nearly the same as that of eustatic emergence. Writing on the subject of "warping and gentle arching", or "undulatory" uplift, Andrews[1] remarks: "No geologist conceives the Eastern Australian plateau as being raised to a uniform height. Such a structure would produce a series of towering precipices of uniform height at the place where the sea or the inland plains intersect them." In Australia warping has made strong relief in some districts, and there are some breaks in the surface due to great faults. In the northern Appalachian region of North America Barrell believed he found evidence of "progressive doming at an irregular rate combined with recurrent phases of emergence or submergence",[3] though doming is not recognised in Meyerhoff's later interpretation.[29]

Theory of Base-level Control Questioned

In contrast with the point of view more generally maintained that peneplains have developed in relation to base-levels of the past, Sauer[35] favours the idea of denudation in the sense of surface wastage (German, *Abtragung*) producing a peneplain at a high altitude, while this is preserved in some unexplained way, for the vast period the process requires, from dissection and destruction such as normally follow headward erosional development of the valleys of rivers that drain to lower levels. The "primary peneplain (*Primärrumpf*)" that he diagnoses as forming the level summit areas of Mesa Grande and Julian Mesa, and in general of blocks of the Peninsular Range of Southern California and its farther southward extension, he characterises (with the utmost confidence in the theory) as

not, in so far as is known, a surface once worn down to a low level and then uplifted, but an assemblage of forms which, though at summit position, is in process of reduction of relief. . . . Of the antecedent surface . . . nothing further is known. . . . The area has been subject to subaerial denudation indefinitely, perhaps since Mesozoic time. It has long ago become detached by uplift from any base-level of erosion extraneous to the local block, if such connection once existed. The surface slopes established in the initial up-movements . . . have propagated themselves inward across the mesa.* The interior . . . has been growing more subdued as to surface at the same time that its margins have increased in slope and height. . . . It is probably . . . still rising. (SAUER.)

PENCK'S THEORY OF PIEDMONT BENCHLANDS

On the horsts, massifs, or torsos (German, *Rümpfe*) of deeply eroded ancient rocks forming mountain ranges in Europe summit-levels have been observed to indicate the existence of benched profiles on the flanks of the mountain masses similar to those brought to light by projected-profile and statistical studies elsewhere. "Close observation reveals the new and surprising fact that the heights and slopes of the German mountains are not overstretched by a single peneplain, but that several peneplains are there repeated in step-like succession" (W. PENCK,[31] translated by DAVIS).[13] Both in North America (according to Barrell) and in Germany (according to Penck) the older (higher) benches are somewhat more steeply inclined than the younger (lower), this relation contrasting, it may be noted, with the "concordant" succession of valley profiles found in France by Baulig.[6] Associated with the peneplain benches in the German mountains indications have been noted of successive rejuvenations of rivers working upstream into the mountain masses.

The explanation offered by W. Penck[31] and his school[10] of the "piedmont staircase", as the succession of down-stepping marginal, or piedmont, benches has been termed, and of the valley features associated with it contrasts strongly with the French and American hypothesis of successive cycles of erosion developing during long pauses in intermittent uplift. Briefly Penck's theory is as follows: The mountain area after being reduced to low relief by earlier erosion underwent *continuous* upheaval as an *expanding dome*—i.e. as a dome with continually increasing diameter at its base, so that

* Theory of W. Penck (see pp. 230-233).

outlying parts, after being for a long time unaffected by the upheaval that was already in progress, were eventually uplifted. It is a part of the theory also that the continuous uplift was of the *accelerated* kind (taking place at an increasingly rapid rate). "The step-like succession of benchlands does not indicate in the least that upheaval proceeds intermittently, but that it is continuously accelerated" (W. Penck).[13, 31] It is supposed to continue through many geological periods.

One of the last tasks which the veteran geomorphologist Davis undertook was that of examining with an open mind this theory of Penck. He arrived at the conclusion that it must be rejected, but apart from this verdict his perfectly fair exposition of the theory is of great value, and may be referred to in view of the importance of the questions raised. The theory as applied to the development of nicks in river profiles is summarised, with interpolations, as follows:

The lower course of the river, having a larger volume and therefore also a greater erosive power than the upper course, will be the first to be able to overcome the increase of its gradient due to accelerated upheaval. Hence as upheaval becomes faster, the larger lower course cuts down faster than before, but the weaker upper course does not. Thus a convex nick is formed in the river profile [at some unspecified point] separating an upper and a lower segment of its graded course. The top of this nick, retrogressively eroded [by the locally steep-pitching stream], serves as a local base-level for the upper segment of the graded course, which is therefore no longer controlled by the more general base-level at the margin of the [expanding] dome. Moreover, the local base-level is, while working upstream, raised with the rise of the dome and therefore rises in relation to the upper segment of the graded course. Hence there the erosive power of the upper stream is weakened, and concave basal side slopes are developed below the higher convex slopes. [In the meantime, the lower segment below the nick continues to deepen its valley and to maintain its course at grade in the margin of the rising dome.] Continued acceleration of upheaval causes the production of a series of nicks, all working headward, in the stream profile. (Davis.)[13]

As regards the "step-like succession of benchlands", the central part of the dome is upheaved sufficiently rapidly to cause its dissection, but its more slowly upheaved margin is worn down by

erosion to a lowland *pari passu* with its uplift, and, as the dome expands, successively eroded marginal lowlands are converted into higher-standing benches undergoing dissection (Fig. 269). Davis has pointed out that the process by which successive benches are supposed to be differentiated during continuous uplift has not been explained; and in view of the systematic arrangement of the benches, their correlation on different parts of the mountain flanks, and their obvious relation to nicks in the river profiles, all demonstrated by Penck's field studies, he remains convinced that such evidences of "intermittent erosion" are to be explained only by assuming that they were developed during pauses in a discontinuous uplift.

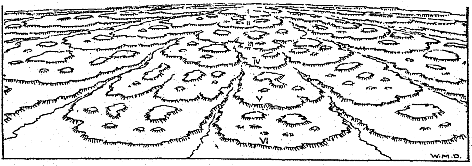


Fig. 269. Conventional diagram (drawn by W. M. Davis) of "piedmont benchlands on a domelike highland".

Penck's theory of the origin of piedmont benchlands has been carefully examined and adversely criticised by Baulig,[8] who contests in particular the claim that the break of slope at the top of a nick of rejuvenation serves as a local base-level.

> Provided that the change in the relative position of the [general] base-level did not appreciably affect the climate and the river gradient, the profile of equilibrium will go on evolving exactly as it has done thus far. It follows that a break of slope is not a peculiar part of a river profile endowed with special properties, and least of all with the indispensable fixity of a base-level. (Baulig.)

Baulig has pointed out, moreover, that Penck's fundamental theory of domical upheaval, which is applied to the Black Forest and all mountainous areas similarly flanked by benchlands, is chimerical. In the Vosges Mountains, a massif which is adjacent to, and the twin of, that of the Black Forest, it is possible to restore almost perfectly on both flanks of the range the pre-Triassic floor, some

facets of which have been resurrected; and this surface, which originally was practically plane and horizontal, may be shown to have been tilted in various directions in different parts and to have been broken by faults, but it affords no evidence of upheaval of the massif in the form of a dome.[8]

Penck's theory failed to receive support from any of the American geologists who took part in 1939 in the symposium "Walther Penck's contribution to geomorphology".[32] Their collective opinion may be summed up in the words of Douglas Johnson,[20] who said: "Penck's conception that such benchlands can develop on a uniformly rising and expanding dome seems to me impossible of acceptance. The reasoning by which he accounts for the development under the conditions he assumes seems invalid." The production of nicks also requires "some cause other than progressive uniform uplift".[20] Leighly[25] also remarked: "I cannot see how *Knickpunkte* can be formed in slopes and in longitudinal stream profiles in a homogeneous mass undergoing continuous uplift."

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CHAPTER XX

Block-faulted Landscapes

No attempt has been made in the foregoing chapters to describe landscape forms that are directly related to the outcrops of faults, though it has been necessary occasionally to refer to fault movements as occurring along with warping and folding in the deformations of the earth's crust and of its surface, not only those that initiate "first" cycles and cycles following long periods of still-stand, but also those that interrupt earlier cycles at some intermediate stage.

Faults, either in the body of the rocky crust or looked at from the viewpoint of the effects of their outcropping edges as influencing surface relief, may occur sporadically, as though minor breaks or tears had been formed at places of exceptional stress accumulation during warping or folding; but, on the other hand, in some regions deformation of rocks and surface has taken place mainly by faulting, which has broken the superficial crust into differentially moved blocks; and a combination of large-scale faulting with strong warping is not unusual. Faults of recent occurrence have been responsible for the initiation of many impressive landscape features that may still be recognised as fault-made in the sequential forms they have assumed as a result of the ravages of erosion.

Complications of the structure of the underlying rocks due to the presence also of faults that are very ancient as compared with the date of origin of any existing surface forms are common in most regions in which folded and deformed rocks of any age are present. Subsequent erosion has resulted in certain circumstances in the development of striking landscape features along the lines of outcrop of such faults, but description of landforms in this category has been reserved for inclusion in a later chapter because of their many points of resemblance to features resulting from recent faulting, such as are now to be described.

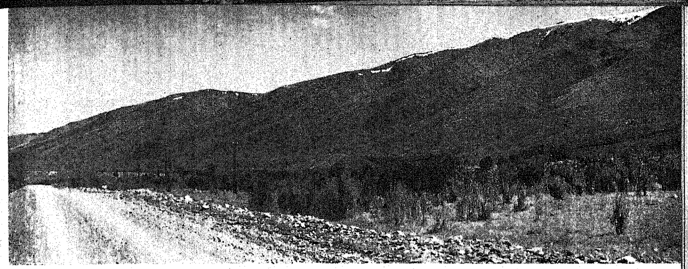


Fig. 270. The Wairau fault scarp, which forms part of the northern wall of the Wairau Valley tectonic depression, in the South Island of New Zealand.

Fault Scarps

Where faulting has just taken place there are actual breaks of the land surface—sudden descents from the high-standing to the low-lying sides of the faults (Fig. 270). These *fault scarps* (Russell)[30] are striking landscape features in the early stages of the cycle introduced by the movements associated with the faulting. In soft material, such as that immediately underlying a newly uplifted sea floor, they are very quickly destroyed by erosion, but they are much longer lived in cycles introduced by uplift and deformation of pre-existing land (i.e. if it is composed of more resistant rocks), and also where newly uplifted marine or alluvial beds are thin and rest on resistant rocks, which are exposed in the initial scarps formed by faults of large displacement.

It is significant that Johnson,[21] who has observed and described such forms elsewhere, has taken occasion to remark that "not a single true fault scarp" is known to exist in the stable New England —Acadian region. Geologists whose field experience has been confined to those regions quite stable in recent geological times, like western Europe and eastern North America, in which fault scarps, in common with all other features that may be produced by very recent and contemporaneous differential movements whether of block faulting or warping, seem to be absent, have been inclined to discount the importance, and even doubt the existence anywhere, of surface features resulting directly from fault movement. The argument has been resorted to that differential movements are essentially so slow that, even if it be granted that faults extend upward to the earth's surface, the development of scarps along their outcrops will be prevented by erosion, embryonic scarps being worn

down as rapidly as fault surfaces emerge. We read in a textbook, for example, that "faults are rarely visible at the surface of the ground as a sharp difference of level, since the processes of erosion usually keep pace with the movement of a fault". To answer such statements it is sufficient to refer to the discussion in Chapter XVI of the similar proposition that peneplains in general develop as surfaces such as may be described as "old from birth". Investigators of the land surface in recently disturbed regions, including western North America, Macedonia, Peru and Chile, western and central Asia, western China, Japan, central Africa, and New Zealand, and even in relatively stable Australia, appreciate the existence of fault scarps as important landscape features.

Geological Proof of Landscape Faulting

The explanation of the origin of the Basin Ranges proposed by Gilbert[19]— as fault-bounded blocks formed at the surface—had been adopted by Davis[15] and shown to be correct for at least some of the ranges of the Great Basin by his critical analysis of the geomorphic evidence. Though other competing theories had been thus disposed of, Davis, however, welcomed a geological confirmation of his own demonstration. This resulted from the work of Louderback,[22, 23] who was able to show that dislocated parts of lava sheets found on the back slopes of certain blocks had been formerly continuous. The lava had spread over a surface of small relief, and the compound mass so formed had afterwards been broken into blocks which carried up with them segments of the lava covering. Such differentially moved portions of a lava sheet have been called "louderbacks" by Davis, and "louderbacked" block mountains are not uncommon. Davis[17] has described examples of louderbacks on the Peacock Range, Arizona (Fig. 271), and in south-eastern California, where they are conspicuous on the step-faulted Argus Range.[20a]

The discovery of louderbacks not only proves the rapidity of movement in block faulting as compared with that at which emerging scarps are destroyed by erosion, but also demonstrates the recency of the faulting involved. Louderback has dated the beginning of the great displacements that have upraised some of the high fault-block ranges of the Great Basin region as late Pliocene or post-Pliocene.[23, 24] Some great blocks in south-eastern California

began to rise only in the early Pleistocene.[20a] In that region and in New Zealand numerous new scarps and scarplets on the land surface indicate repeated movement on faults up to the present day.

Fault Blocks in the Landscape

In block-faulted regions of tectonic relief faults commonly occur in groups, the members of a group being parallel to one another. There may be two intersecting systems of such fractures, which cut the landscape up into quadrilateral *blocks*. Commonly, however, the blocks that have risen or subsided (relatively), or assumed tilted attitudes independently of one another, are elongated, and their

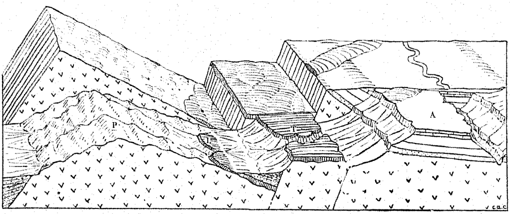


Fig. 271. Louderbacks of the Peacock Range tilted block, P, Truxton Mesa step-fault block, T, and faulted margin of the Arizona plateau, A. Potential initial forms at the rear and actual forms in the front strip. Dislocated parts of a lava sheet are seen on all three blocks. L, louderbacks on the Peacock Range. (After W. M. Davis.)[17]

terminations may be either cross faults or warped surfaces, as represented in Figs. 272, 285. Such blocks may sink or rise uniformly (movement relative to adjacent blocks only being taken into account), becoming in the one case a trough (*G*, Fig. 272), or *graben,** or in the other an uplifted block (*H*), or *horst,* bounded on the two long sides by fault scarps. Some, however, are *tilted blocks* (*T*), with one side uplifted and the other depressed (relatively). A tilted block is limited by a fault scarp on the uplifted side only, and from the crestline of this scarp an inclined *back slope* (*S*) of tilted land surface descends, to abut generally against the base of the scarp of the next upland block in a *fault-angle depression* (*F*).

* The expression "rift valley", used by J. W. Gregory[20] for large grabens with topographic expression in Africa is accepted by some as a substitute for "graben". As shown by Johnson,[21] "rift valley" does not necessarily have this meaning.

Examples of a horst, a tilted block, and a fault-angle depression, from the Otago block-faulted district of New Zealand are shown in Figs. 273, 274, and 275. In all these the smooth upland, or block surface, which contrasts with steep fault scarps, is either the extensively resurrected fossil peneplain of that region (Chapter XVII) or the peneplain that slightly bevels that surface in some places. Part

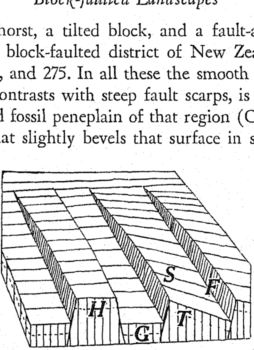


Fig. 272. Elongated fault blocks.
(From *Geomorphology,* also by the author.)

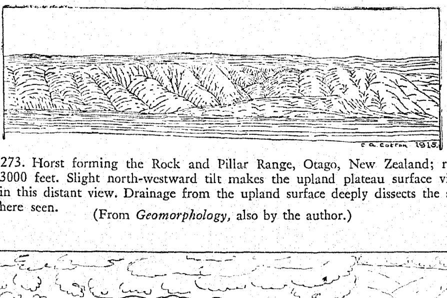


Fig. 273. Horst forming the Rock and Pillar Range, Otago, New Zealand; relief, 3000 feet. Slight north-westward tilt makes the upland plateau surface visible in this distant view. Drainage from the upland surface deeply dissects the scarp here seen. (From *Geomorphology,* also by the author.)

Fig. 274. Small tilted block at Kurow, in the complex graben of the Waitaki Valley, New Zealand; relief, 1000 feet. (Block B in Fig. 287; view looking south-west.)
(From *Geomorphology,* also by the author.)

Fig. 275. Narrow tilted blocks enclosing a fault-angle depression east of Strath Taieri, Otago, New Zealand. View eastward across one block over the crest of the fault scarp of another.

(From *Geomorphology,* also by the author.)

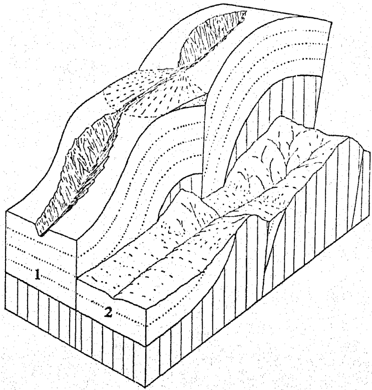


Fig. 276. Origin of the Haldon Hills, New Zealand, and their remarkable drainage. (1) Potential initial form; (2) present-day sequential form.

or all of the stripping of the layer of weak covering beds from the fossil plain has taken place since the uplift with faulting occurred, but the blocks in their present state, though somewhat reduced in size by this erosion, retain almost perfectly the broad outlines of their initial shape.

When some warping of the surface accompanies faulting, fault blocks grade into anticlinal uplifts, and in New Zealand tilted blocks especially have their place taken in some districts by asymmetrical anticlinal folds of the surface, with a reverse fault instead of an overturned limb on the steeper side. Maturely dissected residuals of such tectonic blocks form the Kaikoura Mountains (Figs. 132, 178) and also smaller ranges in their vicinity[13] (Fig. 276).

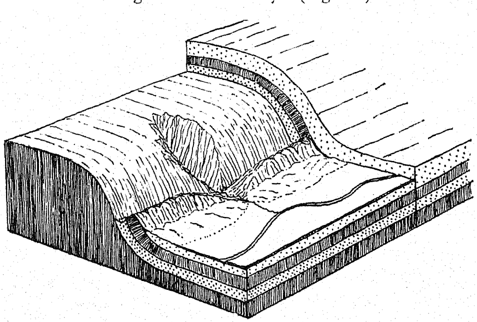


Fig. 277. Erosional development of a steep monoclinal scarp in New Zealand, which in places separates the tectonic Pikikiruna Range block from that of the Takaka Valley (compare Fig. 325). The structure of the soft Tertiary strata, which lie on an undermass of hard Palaeozoic rocks, indicates that the scarp is monoclinal. (Structure after Wellman.)[35] Actually the undermass is dissected beyond the stage shown in the diagram.

Monoclinal Scarps

Faults and fault scarps in places pass lengthwise into monoclinal flexures and warped surfaces (Figs. 277, 278). Willis[36] notes a tendency for thrust-fault scarps especially to pass into monoclinal scarps, but faults that are known to be normal die out into flexures also in the plateau province of western North America.

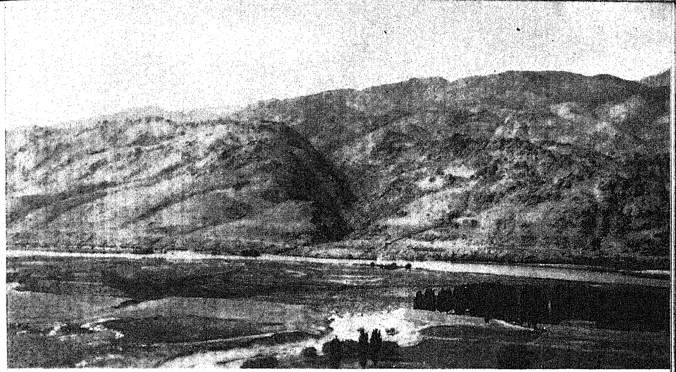


Fig. 278. Monoclinal scarp facing the Upper Clutha tectonic basin at Cromwell, New Zealand.

As a surface feature a steep monoclinal flexure comes closely to resemble a fault scarp after the initial form has been rapidly obliterated by erosion. More gently inclined monoclinal scarps are less rapidly dissected, however. They grade into the warped and inclined surfaces of arched or domed uplifts, and are recognisable owing to the presence of bottle-necked valleys dissecting them, which are separated by flat-iron-shaped facets of the tilted surface (if it was formerly of small relief). A very large-scale example of a monoclinal scarp bounds the Blue Mountains of New South Wales on the eastern side, where the peneplain (in part a structural plateau) of the Blue Mountains is warped down towards the coast. The strongly warped surface is divided into segments by the great escarpment-bounded bottle-necked valleys of the Cox and Grose rivers[32, 33] (Fig. 118).* Rather steep monoclinal scarps dissected submaturely by bottle-necked ravines are common in the Otago district of New Zealand[10] (Fig. 278).

Thrust Scarps

In regions deformed by compression "thrust scarps" are developed along the outcropping edges of thrust-fault surfaces, and these retreat in the form of great structural escarpments if resistant rocks have been thrust at a low angle over weak formations, as in the case of the eastern slope of the northern Rocky Mountains, in Montana,

* See also Barrington Brown and Debenham, *Structure and Surface*, 1929 (Fig. 74).

which is interpreted by Willis[36] as the scarp of the Lewis thrust. Even in the absence of such a pronounced escarpment-making arrangement low-angle thrust scarps may be worn back with a more scalloped outline in plan than the scarps of normal and of more nearly vertical reverse faults.[37] Apart from this they will be geomorphically indistinguishable when mature. While young, however, the scarps formed by thrusting at either a high or a low angle may be recognisable by a development (on a great scale, if the scarps formed are high) of landslides from the overhanging edge.

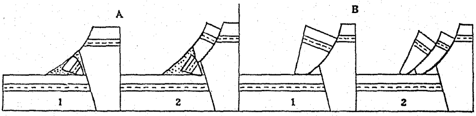


Fig. 279. Landsliding from a thrust scarp. (After Fuller and Waters.)

There may even be, it has been suggested, a separation as "splinters" of minor fault blocks that give way along normal gravity faults of the landslide type, and "it is a fair question whether fault splinters and normal-fault blocks, . . . attributed to rifting of the normal type, may not in some cases at least be the result of large-scale landslips on the imperfectly supported front of a thrust block" (Johnson).[21] This explanation has been suggested by Wayland[34] to account for the appearance of gravity faulting along the boundaries of the Lake Albert graben, or "rift valley", in East Africa, though the main fractures determining the scarps may be thrusts.* The hypothesis has been rejected, however, for the origin of the young lava blocks, great and small, of southern Oregon, in favour of an explanation entirely by normal faulting.[18] In Fig. 279, *A* (1, 2) represents separation of the first two of a long succession of small blocks or strips from an overhanging scarp as it emerges. These will fall and lie in all attitudes and be buried in the debris of crumbling. It has been argued that the development of step-faulted

* Whether the complex elongated grabens that make major landscape features in East Africa, the Red Sea, the Dead Sea, and elsewhere have been opened by gravity or compressional faulting is a question that cannot be discussed here; it is still debated, but few objective descriptions or critical discussions of the fault scarps that descend to these downthrown strips are as yet available.[21]

blocks of large size, *B* (1, 2), requires that a great overhanging scarp shall remain suspended and unsupported during its emergence until a large-scale landslide breaks away from it.[18] It seems possible, however, that support might be afforded by an apron of detritus (*A*, 2) overridden by the emerging thrust scarp until landslide faulting on the required scale could take place.

Some Block-faulted Regions

The vast Basin Range province of western North America, if Gilbert's[19] widely accepted interpretation of it is correct, exhibits faulted, or tectonic range-and-basin, relief throughout; but in some

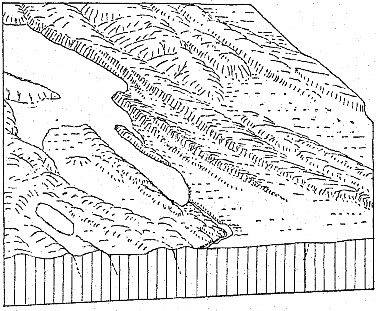


Fig. 280. Young fault-block landscape of narrow tilted lava blocks, forming eastern shore of Upper Klamath Lake, Oregon. (Copied from a block diagram of a larger area by Erwin Raisz, in Johnson.)[21]

parts of it the block forms have been very considerably modified by erosion. In south-eastern California and Nevada there are some very recently upheaved and therefore very fresh, little changed blocks;[20a, 23] but it is the lava-covered region of southern Oregon and north-eastern California that affords the best-known example of an extensive and very young block-faulted landscape (Figs. 280, 281) with consequent lakes on the lowest parts of the relatively down-faulted blocks and with very little modification of the initial forms by erosion.[18, 21, 27, 30]

Rich[29] states that the western slope of the Andes is a "block-faulted land of short ranges and basins . . . Movement is still active in places. . . . In southern Peru and northern Chile recent fault scarps . . . were observed". The "Pampean" ranges, east of the Andes in Argentina, he describes as rising "as fault-bounded blocks above a mantle of late Tertiary and Quaternary gravels and sands".

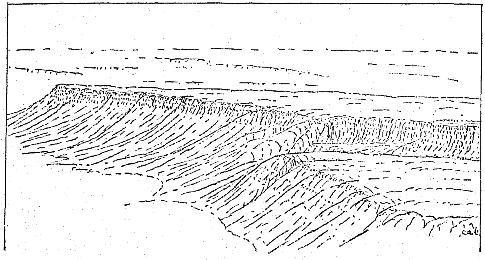


Fig. 281. Young lava horsts, Steens Mountain, Oregon. (Drawn from a photograph)[18]

Southern Macedonia is another block-faulted land in which consequent lakes of considerable size still remain on the downthrown blocks. These date from the "end of the Tertiary and beginning of the Quaternary periods, when the whole of the central Balkan Peninsula was convulsed . . . The entire rock base . . . became partitioned into blocks . . . The separate basins continued to hold water, and as the level of this gradually sank the lakes became isolated".[26]

Eastern Australia is broken into large blocks which are separated by fault scarps and warped surfaces or monoclinal scarps.[32, 33]

In that region the Kosciusko (end-Tertiary) epoch of upheaval was accompanied by extensive normal faulting and warping, some of the faults having a vertical throw of at least 3000 feet. The more important and the greater number of these faults and warps strike approximately north and south . . . The development of these faults produced a series of great fault blocks, the surface of each of which

is part of the Great Eastralian peneplain. In some localities . . . relatively narrow fault blocks are bounded on either side by much higher blocks, thus forming "rift valleys" or *Senkungsfelder*.* (SUSSMILCH).[32]

A block-faulted landscape in South Australia, part of the Mount Lofty Ranges, is shown in Fig. 282.

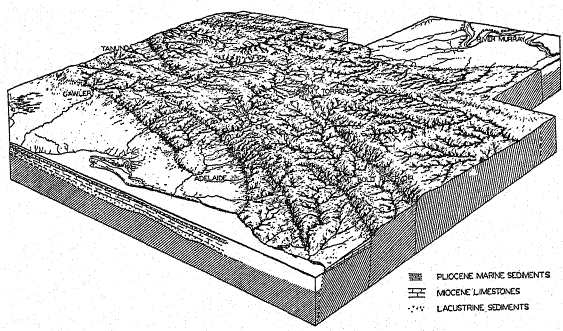


Fig. 282. Block-faulted landscape of the Mount Lofty Ranges, South Australia, showing step-fault descent to the St Vincent Gulf graben, or sunkland. (After Sprigg.)

In New Zealand, almost throughout the South Island and in a large part of the North Island, the major relief is of the tectonic range-and-basin kind (Figs. 273-5, 283-4, 286-8), though modified by erosion to a greater extent in some districts than in others.[4, 6-14] In those parts of the region where covering strata, mainly of Tertiary age, have been present though they have not been very thick the cover has been stripped away from the surface of the higher tectonic blocks (Chapter XVII), and where there has been a substantial proportion of undermass in the upraised blocks and arches the landscape is still dominated by the tectonic forms of relief.[12, 14]

* Term defined by A. Penck, *Morphologie der Erdoberfläche,* 1894 (I, p. 196), to include grabens. Sometimes anglicised as "sunklands".

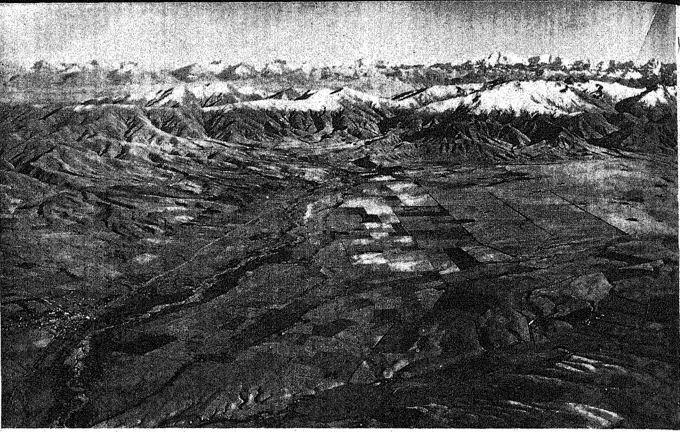
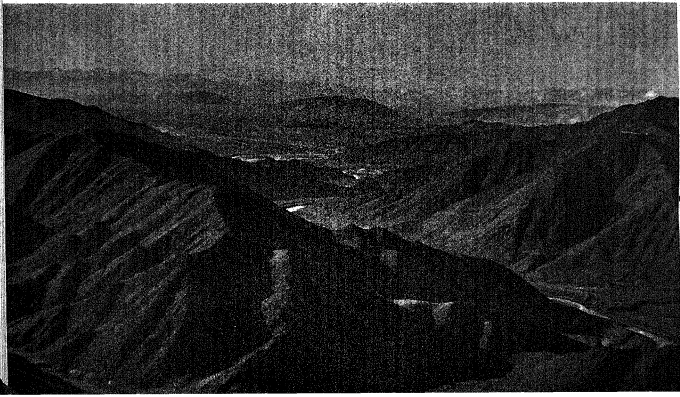


Photo from N.Z. Aerial Mapping Ltd.

Fig. 283. Ranges and basins of the tectonic major relief in South Canterbury, New Zealand. Beyond the Fairlie basin plain is the Two Thumb Range block, with north-and-south elongation; and beyond that are the Mackenzie Plains (a large tectonic basin) and the main range of the Southern Alps. View looking west.

Fig. 284. Outlet gorge of the Waitaki River, through an upland block complex, from the Mackenzie Plains tectonic basin, South Island, New Zealand. View looking north-westward upstream. *V. C. Browne, photo*



The Geomorphic Cycle in a Region of Tectonic Range-and-Basin Relief

In a cycle of erosion introduced by rapid earth movements in which faulting is prominent the infantile surface is diversified by ranges that are uplifted fault blocks (*block mountains*) and basins that are fault troughs and fault-angle depressions variously arranged in plan and probably presenting considerable variety of form. The usual features characteristic of landscape youth and river youth will appear, and will survive for a time on a terrain of resistant rocks; but where only unconsolidated formations outcrop the stage of youth will be truncated or even elided as described in Chapter IX.

Lakes may spill over from one tectonic basin to another (Fig. 285) (provided that the climate is sufficiently humid) forming integrated systems of consequent rivers that thread their way among and around the mountain blocks in characteristic zigzags. The lakes are filled or drained, insequent and subsequent streams develop, stream profiles and the surface generally become graded, and the relief of the landscape is progressively reduced and destroyed as it is on other initially diversified surfaces such as have been discussed in earlier chapters.

Consequent Rivers in Range-and-Basin Regions

In western North America the Colorado River, according to the interpretation of Blackwelder[3] (following up a suggestion of Newberry), came into existence quite recently by taking a course as a consequent stream across and through a faulted and warped landscape comprising a string of large depressions of the surface, which became lakes that spilled over from one to another. The integration of drainage did not, however, immediately follow the deformation, for this occurred in a period of insufficient precipitation, but came later, when more water became available at the source of the river and the consequent lakes overflowed instead of being kept down to low levels by evaporation. "In time, enough excess overflow may have developed to fill a series of basins all the way to the Gulf of California, thus forming a chain of lakes strung upon a river" (Blackwelder). Cutting down of the outlets as gorges has resulted in the drainage of all the lakes, and this has been followed by erosional destruction of lake-shore and lake-floor features.

It is probable that in many cases of uplift with fault deformation, whether affecting pre-existing landscapes or sea floors or other constructional surfaces, no consequent lakes have been formed, at any rate under humid conditions of climate. Deformation probably never goes on so rapidly that erosion accompanying the uplift of blocks may be ignored even on a terrain of resistant rocks, and if rivers run they will cut gorges through some blocks as they rise. Depending on the rate of deformation in relation to the rate at which rivers can deepen their valleys, however, there may commonly be some development of small temporary lakes, though far short of

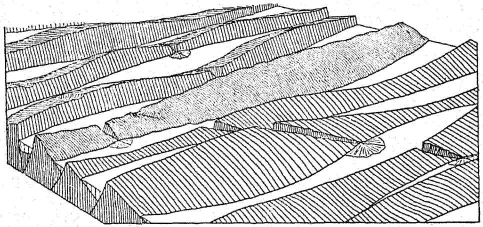


Fig. 285. "Little-modified potential surfaces of diversely tilted and warped blocks . . . in a humid region. The slope of the middle block is drawn to show its pre-faulting surface of low relief. The other block slopes are drawn as if the pre-faulting surface had been a plain. Consequent transverse gorges have been cut across sags in the crests of three background blocks by the outlets of consequent lakes. Oblique gorges have been cut in line through three foreground blocks, irrespective of their height and slant, by segments of a persistent antecedent river, the defeated work of which in three other blocks is indicated." (After W. M. Davis, *Journal of Geology*, 38, 1930.)

occupation of all rock-rimmed basins by water to their full uneroded extent. Erosion also will be very active on all the steep slopes of rising blocks, supplying much waste, which will be deposited, temporarily at least, in the depressions, so that gravel-built basin plains may entirely or almost entirely take the place of consequent lakes.

The outflowing streams from a system or chain of lakes resulting from hypothetically instantaneous strong deformation, and also the integrated systems of valleys of which the lakes for a time formed a part, would be entirely consequent; and if the relief prior to the deformation were small, or the surface plane, even a small amount

of instantaneous deformation would produce the same result. In the case of slow deformation, however, of a former land surface some antecedent rivers may persist in their courses and cut gorges through rising fault blocks, though others are defeated (Figs. 120, 285).

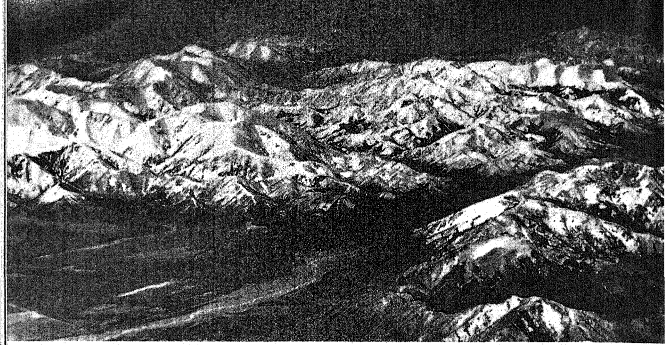
Anteconsequent River Courses and Gorges

The widely different stages of youth, maturity, and old age to which blocks in the North American Great Basin have attained as a result of erosion and degradation since their uplift indicate that in that extensive geomorphic province deformation by faulting has gone on intermittently throughout a long period. Though such attenuation of the period of deformation need not be regarded as always associated with fault movements, it is probably never the case that all members of a group of blocks rise simultaneously and continuously until they assume their final elevations and attitudes. Even in the case of any single elongated block it is extremely probable that some parts have risen before others. Thus some rivers that were strictly consequent on the earlier spasms of movement in a writhing uplift, and became fixed in gorges owing to their activity in downcutting, eventually do not occupy the lowest sags in the crests of blocks over or through which they flow. Such courses are anteconsequent (Chapter XI).

Through grabens and along fault-angle depressions stream courses of a block-faulted landscape will be mainly consequent, and these reaches will be linked together by the gorges of transverse consequents, anteconsequents, and perhaps some true antecedents (Fig. 285), though, of course, these last will not appear in a first-cycle landscape. A river claimed by Davis[16] as antecedent to uplift is one that "holds its course" through the Canyon Range in southwestern Utah. Anderson[1] has described air gaps cut across tilted fault blocks in the northern Rocky Mountains by rivers which have been eventually defeated after following antecedent courses for a time.

River Patterns

The patterns of river systems thus made up are generally irregular and zigzag, for consequent courses in the depressions may be very roundabout where they skirt and avoid the higher blocks of the mosaic. The rivers of the southern and northern ends of the South Island of New Zealand, where large tectonic features are



V. C. Browne, phot

Fig. 286. This view north-eastward across the north-eastern part of the South Island of New Zealand shows mountains which are still young in a cycle that began with uplift of large tilted blocks. The Kaikoura Ranges, on the distant skyline, still preserve the tilted-block form with dissected back slopes towards the north-west. The course of the Clarence River (Fig. 121) zigzags around these blocks. (Compare with Fig. 225, p. 293.)

prominent, afford good examples of such mainly consequent and rather roundabout courses on a block complex (Fig. 286).[7, 8]

Some river courses and some conspicuous landscape forms conform to the fault pattern in a remarkable fault-block complex in the graben valley of the lower Waitaki River, in the South Island of New Zealand[9, 25] (Figs. 287, 288). The course of the main river is here a consequent one through the graben, and some tributary streams are similarly guided, while others follow consequent (really superposed consequent) courses down the slopes of tilted blocks. One, however, the Awakino, traverses an upheaved (tilted) block (block B in Fig. 287) in a gorge that must be classed as either antecedent or anteconsequent, probably the latter (Figs. 288, 289). A similarly developed gorge, in this case in the course of a main river, is the Taieri Gorge, peculiarly placed at the mouth of that river, as shown in Fig. 290, and there is another close to the mouth of the Waiau River of North Canterbury (Fig. 290A).

An example of a New Zealand river course that is interpreted as consequent in a fault-angle depression is that of the Hutt River, at Wellington. The straight course of this river south-westward along the base of the Wellington fault scarp (Fig. 298) cuts obliquely

Fig. 287. The structure of a block complex or complex graben followed (from north-west to south-east) by the lower course of the Waitaki River, South Island of New Zealand. Some of the tectonic blocks, A, B, C, D, of various sizes, can be recognised in the photographic view Fig. 288. In the diagram the undermass of the blocks is shown, stripped of cover, and the uneroded fossil-plain surface of the undermass is ideally restored. (After Marwick).[25]

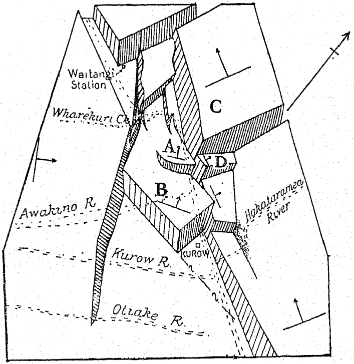


Fig. 288. View of part of the block complex shown in Fig. 287. The lake has been impounded in a wide part of the Waitaki Valley graben by a hydro-electric power dam. Block A (as in Fig. 287) is seen at the upper left corner of the view; the high scarp seen across the lake is that of block C; and blocks B and D can also be identified. The narrow valley traversing block B in the lower right corner of the view is the gorge of the Awakino stream (compare Fig. 289). View looking north. *V. C. Browne, photo*

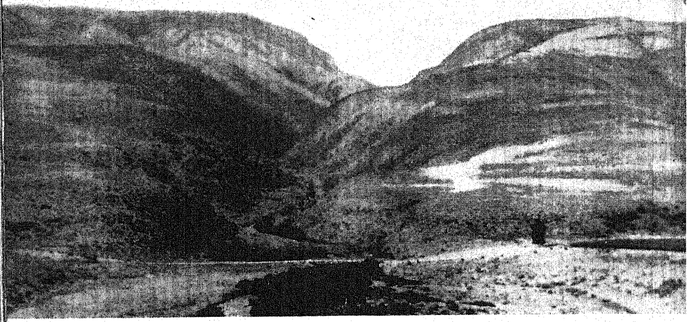


Fig. 289. The bottle-necked gorge of the Awakino stream across block B (in Figs. 287, 288).

across the grain of the terrain, to which much of the drainage of the district has long been adjusted, and as a result the Hutt River receives along its left bank tributaries with sharply barbed junctions.[5]

Some very fine examples of rivers consequent on the slopes and fault angles in a mosaic of recently uplifted and tilted blocks are found in Japan, notably on the Boso Peninsula, near Tokyo[38] (Fig. 291).

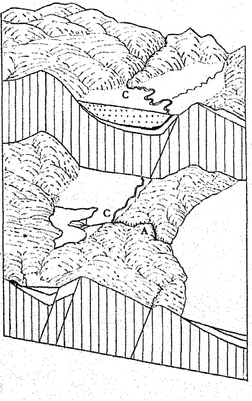
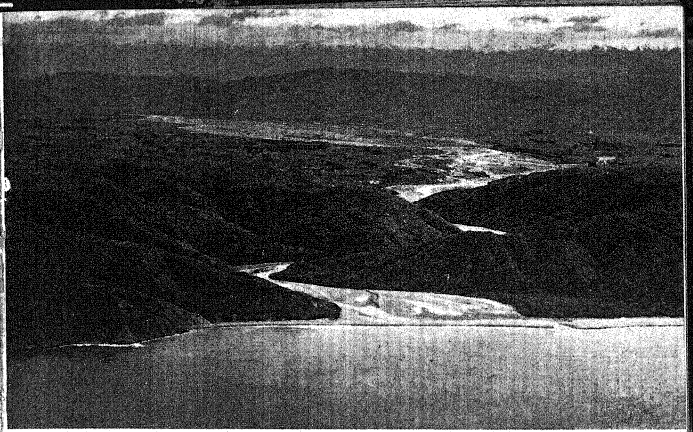


Fig. 290. Part of a block complex in southern New Zealand, showing a consequent reach (C, C) of the Taieri River and the probably anteconsequent Taieri Gorge (A) near the mouth of the river. The surface in both upper and lower parts of the diagram is the present-day landscape. (Copied from a block diagram of a larger area prepared by Professor W. N. Benson.)



V. C. Browne, photo

Fig. 290A. The Waiau River, east coast of the South Island of New Zealand, cuts through an upheaved block near its mouth in an antecedent or anteconsequent gorge.

Features of a Post-Faulting Cycle

The tops and back slopes of horsts and tilted blocks that become block mountains may be eroded surfaces of an interrupted cycle of erosion, or may be plains of deposition, either uplifted portions of the sea floor or alluvial plains. In the former case rejuvenation will go on rapidly because of either tilting of the surface or the development of steep marginal slopes bounding a small uplifted area.* Where the surfaces are initially smooth or nearly so—being parts either of plains or peneplains—the streams that drain them will be consequent on such slopes and corrugations as result from block uplift except in so far as some pre-existing streams survive as antecedents. Being relatively high-standing areas, the slopes of mountain blocks will be rapidly dissected with development of strong relief, and they will thereafter run through the usual stages of mature relief leading on to peneplanation. Block tilting of compound structures in which an undermass of resistant rocks with a planed surface carries on its back a weak-rock cover affords ideal

* The latter apparently self-evident proposition might be questioned by some geomorphologists of the German school. Compare Sauer's theory, stated on pp. 357-8.

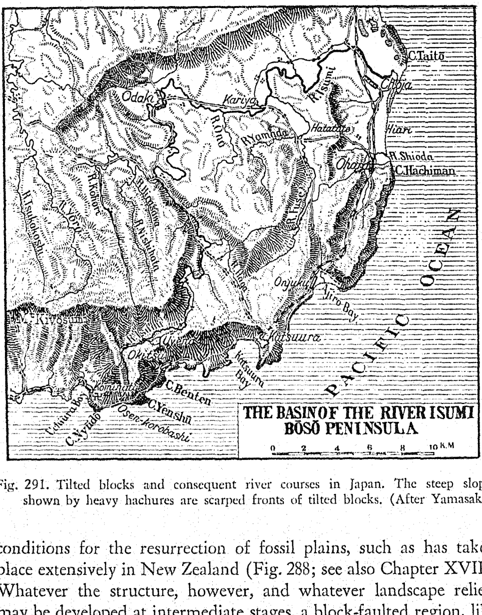


Fig. 291. Tilted blocks and consequent river courses in Japan. The steep slopes shown by heavy hachures are scarped fronts of tilted blocks. (After Yamasaki.)

conditions for the resurrection of fossil plains, such as has taken place extensively in New Zealand (Fig. 288; see also Chapter XVII). Whatever the structure, however, and whatever landscape reliefs may be developed at intermediate stages, a block-faulted region, like any other, must eventually become a peneplain if subjected to erosion under normal humid conditions for a sufficiently long period uninterrupted by any renewal of earth movements.

Problematical Mature and Old Block Mountains

Diagnosis of fault scarps becomes uncertain when they have become maturely dissected (Chapter XXI), and when maturity passes into senility and the block front is worn far back all purely geomorphic criteria of faulting fail. In those parts of the Basin Range province of North America—New Mexico, Southern Arizona,

and Sonora—where there have not recently been any great differential earth movements differences of opinion have developed as to whether the ranges and basins of the landscape were or were not initially fault blocks as Gilbert[19] and many others have believed. Under the prevailing conditions of semi-arid weathering and erosion steep slopes bound the surviving remnants of the ranges, and smooth piedmont slopes of gentler inclination, which are in part bahadas and in part pediments of arid and semi-arid erosion, fringe their bases.[15] If there are great faults that have determined initial scarps from which the present worn range-fronts have been developed, they lie far out under the nearly level piedmont slopes, generally, in fact, at a great depth under bahadas, and the presence of such faults has been questioned.

For the initial forms of typical ranges as developed in the Sonora region and southern Arizona Sauer,[31] on the other hand, prefers to picture upwarps that have been very gradually developed. Such an initial form is a *Grossfaltung* as defined by Walther Penck,[28] who has classed all the Basin Ranges as "Andean ranges" of such origin, along with congeners in South America. The gist of the theory is that upheaval continues slowly throughout several geological periods.

In the case of ranges possibly bounded by faults now concealed any alternative hypothesis deserves consideration on its merits, but the block-faulting hypothesis cannot be discarded without good reason. It is at least as good as that of *Grossfaltung* in cases where the evidence is negative as regards either. The fact remains that throughout a substantial proportion of the vast area of the Great Basin the fault-block nature of the ranges has been established. Demonstration is naturally confined to those parts in which vigorous movement has been in progress comparatively recently. These are, notably, eastern California, southern Oregon, Nevada, and Utah.[23] Geomorphic evidence has contributed to the demonstration in such cases. In its absence there is commonly doubt as to the age of faults; and there are many faults, some of them of great displacement, in the rocks of these ranges that date back to periods of earth movement long anterior to the initiation of the present-day relief (as indicated in Fig. 337, p. 439).

The peculiar theory of Keyes, discussed fully by Louderback,[23] which attributes all the present relief of the Basin Ranges to differential aeolian erosion, merely pushes back their fault-block origin—

quite unwarrantably—to a former cycle. To quote Louderback,[23] who has satisfied himself that the ranges in Nevada and at least some of those in Utah were new fault blocks at the initiation of the present cycle: "As to the extent to which the results of this deformative process [block faulting] dominate the mountain structure of the whole of the Great Basin further evidence is necessary"; but he "is convinced that ranges of this type are common and are characteristic of the region", and he has "no reason to doubt that they constitute the dominant type" nor to think "that the term 'Basin Range type' is in any way a misnomer".

To quote Davis also on the subject of the worn-down ranges:

There is no direct proof that these greatly consumed masses began the cycle of erosion which they have so nearly completed as upheaved fault blocks; such a beginning for them is suggested only because other less consumed masses in their neighbourhood give evidence of that origin.[17]

Great ranges that resemble the North American Basin Ranges are reported in the Altai region of central Asia. They have been progressively rejuvenated during the Tertiary era, and the basins associated with them have been progressively filled to a great depth; but Berkey and Morris[2] have found that the ranges and basins have been formed by repeated block faulting on a large scale.

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CHAPTER XXI

Fault Scarps and Earthquake Scarplets

THE CHARACTERISTIC FEATURES OF BLOCK-FAULTED REGIONS ARE THE actual *fault scarps,* so named by Russell,[26] that mark the outcrops of some fault surfaces extending underground to great depth.*

EXPOSED FAULT SURFACES

It is very unusual to find any large uneroded part of an extruded fault surface, but there are records of the discovery of small areas of such surfaces bearing the slickenside markings that result from fault movement underground. In the very young block-faulted lava region of Southern Oregon, for example, on an almost undissected scarp facing Upper Klamath Lake (Fig. 282), "we have preserved that rare phenomenon, a portion of the actual fault plane of a fault-block mountain". The rock face so described by Johnson[15] (and mentioned and figured also by Gilbert)[11] had been preserved under a layer of superficial debris, and so retained the polished and scored surface due to faulting until laid bare by road-making operations.

SLOPES OF INFANTILE FAULT SCARPS

Gilluly[12] and some others have come to the conclusion that, even where nearly unbroken, wall-like scarps approximately coincide at the base with fault lines, they yet slope back in most cases at angles much gentler than the dips of the fault surfaces to which they are related. The common condition in the fault scarps of western North America is intermediate between the cases (*a*) and (*b*) in Fig. 292. The fault surfaces, though commonly steep, are in few cases nearly vertical and in examples described and photographed by Gilbert[11] are inclined at about 50° and 60°. Blackwelder[2] records that the observed slopes of undissected (infantile) parts of fault scarps in that region are generally much gentler than observed dips of fault planes, which are commonly between 50° and 90° and

* Description as "escarpments" is deprecated for the reasons stated on p. 128.

rarely less than 40°. Noble[22] has suggested that the lofty and wall-like slopes of great scarps in Death Valley and Panamint Valley, in south-eastern California, are actual fault surfaces (see p. 394), though they slope back at an angle of 35°; but this is doubtful, for renewed scarp-making and transcurrent movement at the base seem related to a more nearly vertical fault. Steep and even overhanging fault surfaces, case (*c*) of Fig. 292, seem to be the rule in New Zealand, where block faulting has resulted in the main from crustal compression.[3, 14]

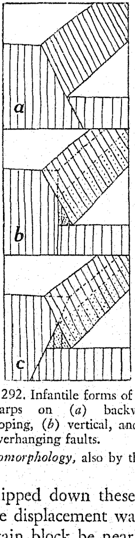


Fig. 292. Infantile forms of fault scarps on (*a*) backward-sloping, (*b*) vertical, and (*c*) overhanging faults.
(From *Geomorphology*, also by the author.)

Crumbling of the edge may, if the debris is removed from the base of the scarp by a river, or if it is progressively engulfed on a sinking block,[2, 22] cause the crest of a very steep scarp to retreat until the base of the resulting slope, which in such cases includes very little talus, is at or close to the fault line before the scarp is subject to much dissection by ravines. Thus it may be imagined that the scarp at the infantile (undissected) stage, or, after dissection has begun, the remnants of it which remain as facets on the ends of spurs, are really landslide surfaces of much less declivity than that of the true fault planes between the mountain blocks, and that great slabs of the steep-faced blocks slipped down these surfaces into the intermont depressions while the displacement was going on; for if the bounding fault of a mountain block be nearly vertical, and if upheaval of the block be relatively rapid, the upper edge of the block might not be able to sustain itself unsupported, and great slabs of it would therefore break off and slide down on the depressed block (Davis).[7]

So Davis wrote in 1921, abandoning his earlier conclusion with regard to the Wasatch scarp.[4] A few years later,[8] however, he was influenced by the opinion of Gilbert,[11] who was then convinced that infantile scarps and, more particularly, the facets on the spur-ends of youthfully dissected scarps present to view the actual fault surface very little modified, even though they may slope at little more than 30°. Gilbert's opinion on this matter was positive after he had made a thorough re-examination of all relevant features along the classic Wasatch scarp, in Utah.[11] The wonderfully smooth facets of this scarp (Figs. 302, 303), which, he became convinced, preserve the form and slope of the fault surface, are inclined at an angle almost uniformly 34°. Gilluly[12] and others, however, doubt the correctness of Gilbert's conclusion and believe the inclination of the main fault surface to be much steeper than that of the facets.

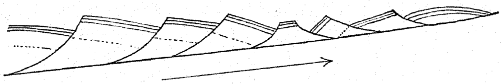


Fig. 293. Section designed by W. M. Davis to illustrate crustal extension due to underdrag and explain inferred low-angle inclinations of initial fault surfaces.

Normal faults inclined at a low angle imply very considerable stretching of the terrain, and this, Gilbert suggested, might occur in the superficial sheet over a hidden underthrust. Here, he wrote, "the master faults are antithetic in type to the overthrust, and demonstrate profound extension of the upper part of the crust."[10]

This hypothesis to account for normal block faulting by crustal stretching due to "underdrag", as he called it, was illustrated in a hypothetical section of Davis[7] (Fig. 293), who made the suggestion[8] that facets sloping gently back like those of the front of the Wasatch Range may be remnants of initial scarps with strongly concave slopes that have been quite steep above in the parts that have been destroyed during the reduction of the fault scarps to their present dissected condition by erosion. Such faulting seems improbable, however, if the faults are normal, as they must be to account for the initial forms of the relief of the land, for it implies an excessive amount of rotation of the downthrown blocks.

Any hypothesis that requires normal fault surfaces to be concave upward may have to be discarded, for, as Washburne[34] has pointed out, fault surfaces must be concave towards the active side. Concavity upward thus implies faulting only of the tensional, gravity, or landslide type and precludes the possibility of upheaval of individual mountain blocks, thus introducing serious difficulties into the interpretation of fault-block landscapes.

As an explanation of steep rejuvenating scarps of the kind that are seen along the bases of the Panamint and Wasatch Ranges (Fig. 306) Davis suggested that "a new fault", such as makes its appearance at the base when the scarp is increased in height by renewed movement, "might be seen as a vertical fracture of the present surface". It would be easier to understand renewed scarp-making movement of this kind as taking place along a new fault that branches from the main fault instead of intersecting it as this hypothesis requires. In the opinion of Gilbert,[11] low scarps that dislocate the alluvium in front of the base of the high scarp of a block mountain mark outcrops of shallow secondary faults which are activated by movement on a gently inclined main fault, and which branch from it, though in an irregular manner, and are, therefore, steeper. It is impossible to account for all minor and relatively steep scarps in this way, however. Alternatively, the main movement, when faulting is renewed, may be concentrated, near the surface, on a new branch fault that diverges at a small angle from the main dislocation.

Embayments in Fault Scarps

Some very high, and still very young, fault scarps in central Washington were found by Russell[27] to be completely mantled with the debris of landslides, which in their case accounted for "many irregular features" and details of the relief. In the stage of infancy, while the crest of a scarp has suffered as yet little or no dissection, large-scale landslides of the slump type may bite out amphitheatres, giving the scarp a scalloped outline. Such amphitheatre-shaped landslide scars diversify a scarp along the shore of Port Nicholson, New Zealand. In this case the landslides must have been engulfed below present sea-level in the Port Nicholson basin before it became partly filled with sediment.

Some irregularity (in plan) of high scarps may be introduced by landsliding, but fault surfaces that are themselves irregular or jagged are unknown. Faults are generally not far from plane, but may be smoothly and broadly curved. Thus, if the faults are steeply inclined, the lines traced initially by their scarps must either be approximately straight or follow broad sweeping curves; but scarps developed along outcrops of low-angle thrust faults are, on the other hand, usually more irregular and may soon become scalloped in ground plan. In Palestine B. Willis[35] has described "the contours of Mount Gilboa and Mount Carmel", scarps descending to the Jezreel-Jordan valley and the plain of Esdraelon, as "sinuous to a degree . . . characteristic of the outcrop of a thrust".

Integrated or Complex Scarps

In the case of scarps in a mosaic that has resulted from normal faulting long and nearly straight scarps may be rare, because gravity faults tend to be short and discontinuous. Some long but somewhat irregular scarps seem to be made up of the scarps of numerous short faults integrated.[12, 22] This is probably true of the Death Valley and Panamint Valley fault scarps, in south-eastern California, which are said to be "exceedingly irregular in detail". Noble[22] further describes them as having a "roughly zigzag pattern", and as "indented by great concave bights or cusps where the offsets occur".

> At some places the bights mark cross faults; at others they appear to represent areas of great and sudden downwarp. At many places the faults exhibit enormous changes in amount of throw in distances of a few miles. Actually the rock masses . . . are a series of tilted crust blocks that have been displaced very irregularly and unevenly. . . . The structure along these great faults is astonishingly complex. (Noble.)

Occasionally abrupt salients are present interrupting rectilinear scarps, and some of these appear to be due not to irregularity of the main fault surface but to the presence of minor faulted blocks or detached and lagging portions of the relatively downthrown blocks that cling to the fault surfaces and have the appearance of buttressing the scarps. Such buttressing remnants have been termed *kernbuts* by Lawson,[17] who has found some forms that may be so

explained bordering the graben valley of the Nile.[19] "Spurs" from the Wasatch Range, which puzzled Gilbert,[11] may perhaps be of this nature also.

High Scarps that are not Dissected

Many low scarps are known in an infantile condition, and some scarps on young Hawaiian volcanoes[31a] make continuous wall-like lines of cliff up to 1500 feet high across the landscape, such as may be pictured as the infantile stage. Examples are known elsewhere of high scarps that are very young, wall-like, and little dissected. There are some in Oregon, including those of Klamath Lakes,[15] one of

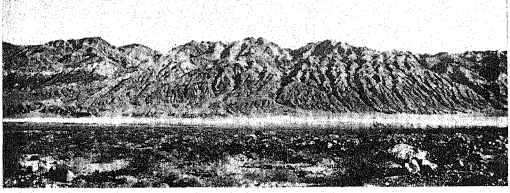


Photo from R. H. Hopper

Fig. 294. Fault scarp, west face of Panamint Range, California.

which has already been mentioned. Other examples are the two great scarps, referred to above, in Death Valley and Panamint Valley, California (Fig. 294). Each of these is, for a length of 35 miles,

> an exceedingly rugged, bare, sloping rock surface that rises abruptly from the valley floor . . . [From a little above the base, where the slope is steeper owing to still more recent faulting it] rises several thousand feet in an extraordinary huge sloping surface whose angle of slope averages 35°. This surface is scored by innumerable parallel ravines which run straight down it . . . Many of them are mere vertical slots in the rock. The surface . . . is continuous. One would like to call it a fault face . . . One who views the surface from a distance finds it difficult to avoid the impression that it represents a . . . fault plane. (Noble.)[22]

As an alternative explanation it may be suggested that these scarps have developed in the manner shown in Fig. 292, (*b*) or (*c*), the

upper part. The absence of talus at the base of the rock slope can then be explained as the result of down-faulting of the foreground, such as is actually postulated by Noble[8] (p. 402) and by Hopper.[14a]

DISSECTION OF FAULT SCARPS

Fault scarps pass through a cycle of stages of dissection simultaneously with the dissection of the faulted blocks of which they form part. The upper surface of a simply tilted mountain block slopes back from the crestline of the front scarp; but if the upheaved block is a horst, or if the upheaval has arched the top surface, this may slope towards a faulted margin. In such a case the scarp receives a considerable contribution of consequent drainage from an upland plateau or arched surface above it, and this flows in extended and consequent courses down the infantile fault-scarp slope, which is, therefore, dissected rapidly and deeply. Even the scarp that forms the front of a backward-tilted block is subject to dissection, however, because of its steepness, though at first the streams gathering as consequents upon its slope must be small, increasing only gradually in volume as they are extended back into the upland above the scarp by headward erosion. Great contrasts are found between the stages of young and mature dissection exhibited by neighbouring scarps that may very well have been initiated almost simultaneously, and in some cases even on different parts of the same scarp, and these can generally be correlated with the small or large part played in the dissection by streams fed from the surface above. Such contrast is found, for example, on opposite scarps of the slightly tilted Rock and Pillar horst, in New Zealand (Fig. 273).

The simple case of the scarp of a backward-tilted block undergoing dissection by streams consequent on its own slope was discussed first by Davis.[4] On such a scarp (Fig. 295), where the first-formed consequent streams on the sloping surface in its infantile condition, as prepared by crumbling and landsliding in most cases, are alone responsible for the formation of dissecting ravines, these will extend back by headward erosion and thus develop notches in the crestline (*B*) dividing it into segments. (Such streams, beginning their existence as consequents, become true obsequent streams when they have gnawed their way so far back into the block that they have reversed the original direction of drainage on part of its back slope.)[6] The *facets*[4] isolated between these

ravines are rapidly reduced in size and changed from rhomboidal to triangular shape as the ravines continue to develop. These triangular facets still bluntly truncate tapering spurs that descend from the upland behind the scarp (*C* or *D*). The bases of the facets, or remnants of the infantile scarp, if not of the actual fault surface, are situated approximately at the fault, and so they trace a simple line (Figs. 295-8).

In a humid climate spur-end facets become rounded at the edges even while the dissection of the scarp is still young (Fig. 296), whereas under arid conditions they tend to retain a sharp-edged character (Fig. 297) in common with all forms that result from rapid dissection.

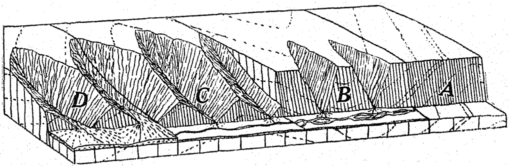
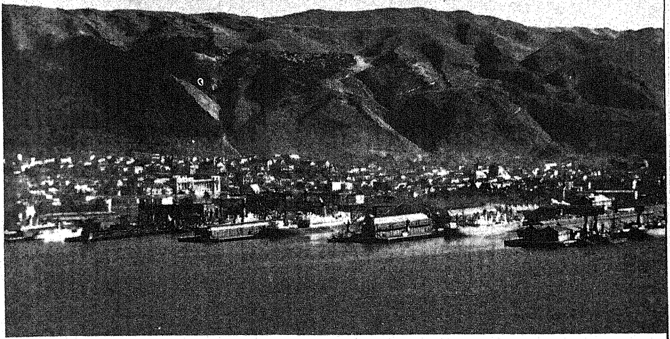


Fig. 295. Dissection of a fault scarp. *A*, initial (or infantile) form; *B*, *C*, *D*, sequential forms. Debris from dissection may be removed by a river, *B*, *C*; or accumulate as fans, *D*.

(From *Geomorphology*, also by the author.)

As dissection advances towards maturity, general lowering of the land surface on the spurs and widening of the lower valleys of the dissecting streams gradually reduce the areas of the facets or blunt spur-ends until the spurs taper practically to points. These may still end in line, however, and very close to the fault trace, and as long as they do so dissection of the scarp has not passed beyond maturity (Figs. 299-301). In contrast with the young fault scarp of the Wasatch Range (Utah) Davis[5] has found that of the adjacent Canyon Range maturely dissected. This range must, therefore, be an older, i.e. earlier upheaved, block.

In old age of the fault scarp the much reduced spurs will be worn back to varying distances from the fault line, all geomorphic traces of which will now be lost.[4]

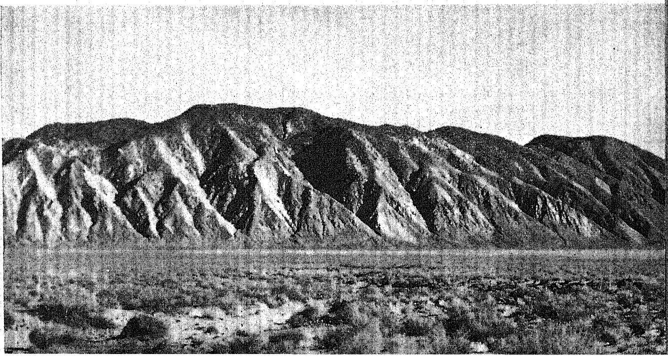


J. W. Jones, photo

Fig. 296. Youthfully dissected fault scarp with blunt-ended spurs strictly in line, Wellington, New Zealand.

Fig. 297. Young fault scarp of a granitic mountain block east of Deep Springs Valley, California. Alluvium covers a down-faulted foreground.

Professor Eliot Blackwelder, photo



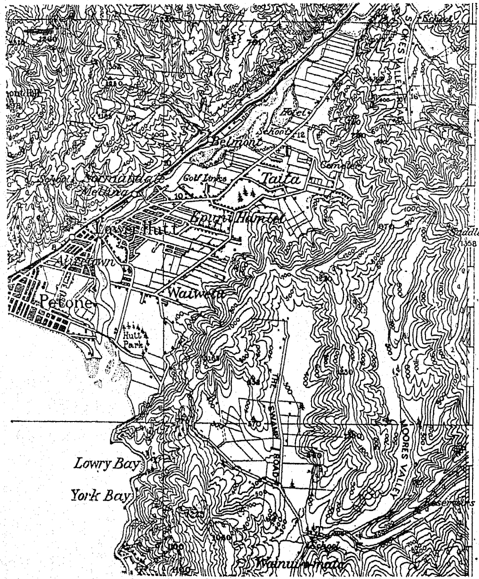


Fig. 298. Simple line traced by a rather recently rejuvenated fault scarp along the north-western side of the Hutt Valley depression, Wellington, New Zealand. The eastern side, in contrast, is embayed, owing to down-warping and aggradation of a mature surface (cf. Fig. 255). Heads of valleys of the Wainui-o-mata system, aggraded owing to headward tilting (Fig. 258), occupy the south-east corner of the area mapped. Scale: $\frac{3}{4}$ in. = 1 mile. (Compare Fig. 335A.)

(From *Geomorphology,* also by the author.)

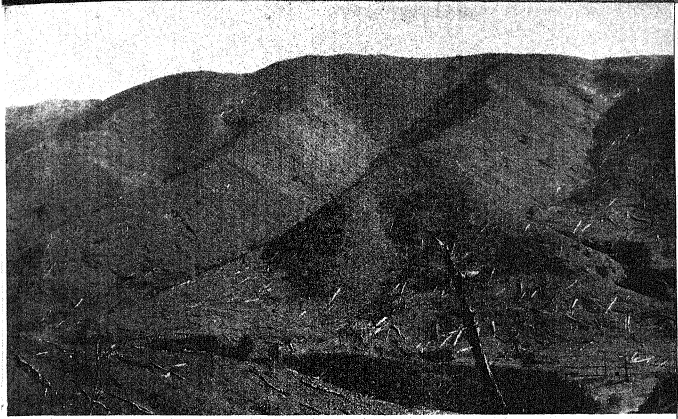


Fig. 299. Maturely dissected fault scarp (in part a fault-line scarp), Ruakokopatuna Valley, Wairarapa, New Zealand.

Scarps in course of dissection may or may not be modified by lateral stream corrasion. Under humid conditions of climate consequent rivers traverse grabens and fault-angle depressions, developing eroded valleys in them and removing perhaps all the debris of dissection of the fault scarps that flank them (Fig. 295, *B, C*). Where such is the case, they cannot fail to corrade the fault scarps themselves, truncating and faceting the spur-ends and cutting them back to alignments no longer related to the fault traces. The problem of recognition of fault scarps is thus complicated, and due allowance must be made for river work.[3] A fault scarp descending to the sea may be similarly much obscured, or obliterated, by marine erosion, as has certainly occurred on parts of the coasts of New Zealand.

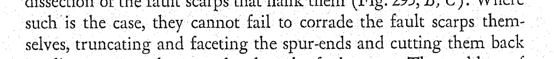


Fig. 300. Maturely dissected southward-facing fault scarp of the level-topped Hawkdun Range, part of the northern highland of Otago, New Zealand. Relief, 3000 feet. All the upper part of the scarp is undoubtedly a true fault scarp.

Professor Eliot Blackwelder, photo

Fig. 301. Maturely dissected fault scarp of the Inyo Mountains (Palaeozoic rocks with granite intrusions) north of Lone Pine, California.

Even wide lateral swinging of streams emerging from a fault scarp on to a bahada may be accompanied by a trimming back by lateral corrasion of the spurs beside them to the extent of developing an erosion scarp, as implied in Johnson's theory of the development of rock fans and pediments (Chapter XII). Fault scarps in arid regions may escape such mutilation in their youth, though subject in maturity to desert back-wearing, or slope retreat. In arid and semi-arid regions, however, much waste accumulates on down-faulted blocks to form basin plains, and growing bahadas fringe fault-scarp bases (Fig. 295, *D;* 301), burying them deeply perhaps, while at maturity aggradation extends up the dissecting valleys.

It has been tacitly assumed in most of the foregoing discussion of fault scarps that deformation and uplift are so rapid that the effects of erosion accompanying uplift may be neglected. This is a simplified case only, however, and it must be recognised that much dissection may, and usually does, take place during a long period of intermittent movement, which, regarded broadly, may be considered to produce the same result as very slow continuous movement.[4] While this is going on the spur-ends are always fresh and little modified—i.e. infantile—portions of the fault surface. Since they are being actively cut down by ravines on each side as they

rise, so that their edges cannot become rounded off, they present conspicuous sharp-edged facets (Fig. 297). Thus, though circumstances may combine to preserve facets after movement has ceased, a conspicuous line of sharp-edged facets on the ends of numerous short spurs, especially where main spurs descending from a high

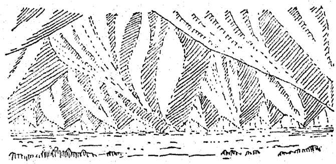


Fig. 302. Facets of the fault scarp of the Wasatch Range, Utah. (After Davis.)

block or range sprawl outward and are divided up by splitting ravines into minor spurs, can generally be taken as an indication of the presence of an "active" fault, and of a scarp that is still growing or has recently recommenced growing. A classical example of such is the western scarp of the Wasatch Range, in Utah (Figs. 302, 303), the sharp-edged facets of which have been described by Gilbert[11] and by Davis.[4]

Fig. 303. Faceted ends of sprawling spurs along the base of the Wasatch fault scarp, Utah.

Professor Douglas Johnson, photo

Some other features that are diagnostic of continued or, at least, of very recent movement are found in basins to which fault scarps descend, but are confined to arid regions. In an arid climate through-going rivers are not present to remove the debris of fault degradation, and this must, therefore, accumulate in front of scarps as bahadas and in the intermittent lakes on basin floors. Fault-block relief results from differential movement between blocks, and, where a fault is active, the movement that reveals a scarp may be wholly or in part a continuation of the subsidence or down-tilting of the block below the scarp. Continued degradation of a scarp after such fault movement has ceased is accompanied normally by growth of the bahada in front of it, so that the axial line of the floor of the depression is pushed away from the fault, but frequent renewal or continuity of the down-tilting movement may keep the axial line close to the scarp base.[2] In such a case the fans at the ravine mouths of a dissected scarp may seem "abnormally" small because the debris of early stages of dissection has been carried down by the sinking basin floor and is lost to view (Fig. 297). Under such conditions alluvial deposits may have accumulated to an enormous thickness in front of a scarp, though surface forms will give no indication of this. It has been observed that, for this reason, a "noteworthy feature" of the scarps of the Death Valley and Panamint Valley faults, in south-eastern California, is

> the utter insignificance, and at places absence, of alluvial fans along their base. At most places the playa flat or salt marsh that occupies the deepest part of each valley [in that arid-desert region] lies directly against this escarpment along its eastern margin, as is shown by the fact that all the small ponds which constitute the sinks of the valley drainage occur directly at the base of the escarpment. The fans on the opposite side of the valley present the strongest contrast. They are enormous features, which border all the west side of each valley in a continuous alluvial apron several miles wide. (Noble.)[22]

It has been claimed by R. Willis[36] that a fringe of fans along the front of a range is an indication that the range front is a fault scarp. The evidence is of some value, but not conclusive, for lines of cliff bordered by alluvial slopes may be formed in other ways (Chapter XV); and the possibility of removal or engulfment of debris, referred to above, rules out absence of fans as evidence against the fault origin of a scarp.

Rejuvenated Fault Scarps

Rejuvenated fault scarps are those which have been freshened by renewed movement after some dissection has taken place in a period of rest (Figs. 304, 305). The newer portion of the scarp may be nearly continuous as well as steeper than the somewhat degraded spur-ends above it, joining these at a distinct shoulder;[5] the dissecting streams, more or less completely graded farther upstream, will have steeper descents and narrower valleys or ravines in their

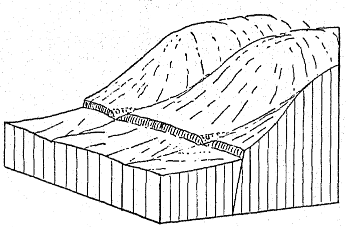


Fig. 304. A rejuvenated fault scarp. (Copied from a diagram by W. M. Davis illustrating a feature of the Lepini Mountains, in Italy.)

lower courses, developing Y, or "hourglass", valleys (seen in Fig. 308). They may even plunge as falls over the edge of a new scarp.[28] Such rejuvenation effects are seen in all the small ravines along the Wellington fault scarp (Fig. 296), though several of the larger streams that cross the scarp are cut down to sea-level at their mouths and are at grade in parts of their lower courses. Even when the newer portion of a rejuvenated scarp itself becomes submaturely dissected, the spur-ends may retain a blunt or faceted form in contrast with the more subdued and tapering forms on higher parts of the same spurs, which may be regarded as parts of the earlier formed and more thoroughly degraded scarp (Fig. 296).

Several successive rejuvenations have affected some fault scarps, notably those of the Death Valley and Panamint Valley faults, where

> the major movement is recorded in the huge 35° rock face . . . ; more recent movements are recorded in the small cliff that meets

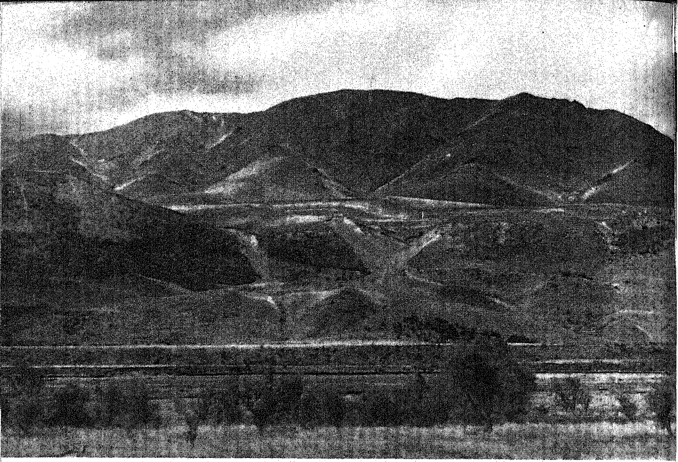
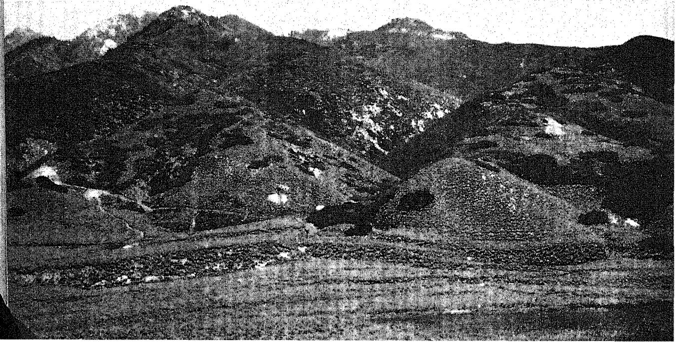


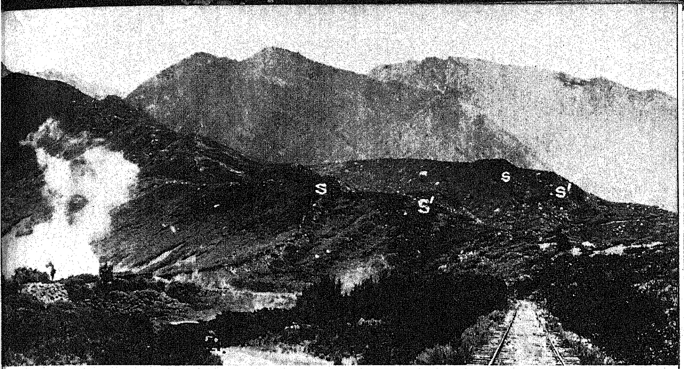
Fig. 305. Parallel rejuvenating scarplets (on the edge of the high terrace) along the base of a fault scarp that forms the southern wall of the valley of the Hope River, New Zealand. These scarplets show some dextral transcurrent as well as vertical movement.

the valley floor at the base of the sloping rock face; and still more recent movements, which undoubtedly are still in progress, are recorded by scarps in the recent alluvial fans at the base of the cliff. (NOBLE.)[22]

Fig. 306. Scarplets in alluvium parallel to the base of the Wasatch Range scarp, Utah.

G. K. Gilbert, photo





Professor Douglas Johnson, photo

Fig. 307. Scarplets across glacial moraines at the base of the Wasatch Range, Utah. Steam rises from hot springs related to the faults. The scarplets are lettered SS and S′ S′.

Earthquake Scarplets

Numerous low scarps of rejuvenation so recently formed as to be as yet untouched by erosion are known in seismic regions of block faulting. Some of these intersect the alluvial fans that fringe older and dissected mountain-front scarps,[5, 11] and to these latter the newly formed scarps are commonly parallel (Fig. 306). Many very recent dislocations of the surfaces of alluvial fans in Death Valley and Panamint Valley (south-eastern California) are reported by Noble.[22] Most of the scarps made by these are less than 20 feet high, but on one large fan there is a graben four miles long and a mile wide which is 400 feet deep in some places. Barbour[1] records that "at several places in . . . Kansu [western China] young fault scarps dislocate the Pleistocene terraces . . . . These pass close to villages that suffered heavily at the time of the earthquake of 1920". At the base of the great scarp of the Wasatch Range, in Utah, low scarps that are obviously of recent origin mark the outcrops of faults that dislocate not only fans of alluvium (Fig. 306) but also late Pleistocene glacial moraines[11] (Fig. 307). The first appearance of some such "scarplets", as Davis and Blackwelder[2] have called them, has been definitely associated with the occurrence of earthquakes (Fig. 308), as Lawson[18] and others have noted.

Professor Eliot Blackwelder, photo

Fig. 308. Scarplet along the west base of the Sonoma Range, Nevada, formed at the time of the earthquake of 1915. It extends for about 40 miles across both spur-ends and alluvial fans, and is from 10 to 20 feet high.

Fig. 309. Scarplet in the Ohariu Valley, near Wellington, New Zealand, the cicatrice of a fault movement that has caused a rather recent (but prehistoric) earthquake. The nearest pole is on the edge of the scarplet, 3 feet high, facing left.

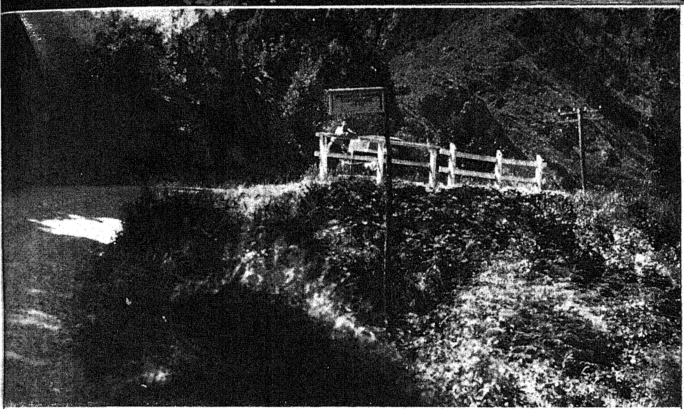
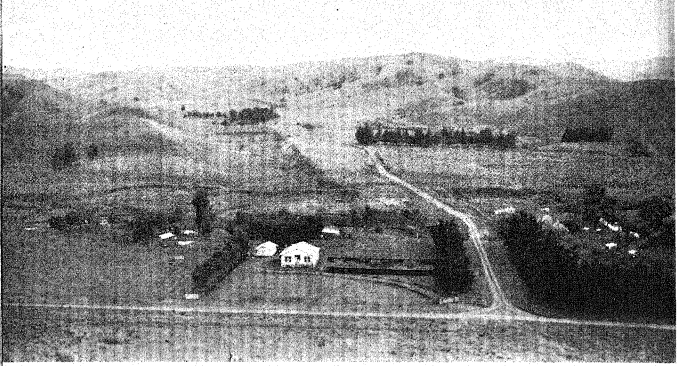


Fig. 310. New scarplet, formed in 1929, which, as here shown, dislocated the road through the upper gorge of the Buller River, New Zealand. A deviation, at left, now ascends to the severed end of the former road, which is fenced with a white railing and supported by a retaining wall.

The centres of origin of the earthquakes associated with the formation of some scarplets have been situated on great faults undergoing rejuvenation, but others associated with earthquakes appear sporadically as though either on the lines of small new dislocations or renewing movement on ancient faults that have been without expression in the recent landscape (Fig. 309). Others again clearly result from locally developed shallow faulting in the vicinity of major dislocations. Of the latter nature were prominent scarplets developed across bedrock outcrops near Nunatak Fiord, Alaska, in 1899.[32] A scarplet caused by fault movement associated with the West Nelson earthquake of 1929 in New Zealand dislocated the course of the Buller River and also the highway between Westport and Murchison, making a step 15 feet high (Fig. 310), without following any prominent lineament of the landscape. The White Creek fault, on which this movement took place, though it is an ancient one of large throw separating Tertiary sedimentary rocks from granite,[9] had been long inactive and could not be traced across the Buller valley as a scarp, either tectonic or erosional. (In Fig. 254 this fault line passes along the neck of the narrowed spur and thence northward across the Buller River at S, where a jog in the line of the road marks the point at which it was dislocated in 1929.)



M. Ongley, photo

Fig. 311. Scarplet near Masterton which is part of the surface trace, or outcrop, of the fault that caused severe shaking in central New Zealand in 1855. The scarplet faces left, in the centre of the view.

Various scarplets in the Southern Alps (New Zealand) have been described by Speight.[30, 31] One of these, seen in Fig. 168, S, dislocates the lowest terraces bordering the Rangitata River. In the districts near Cook Strait also (in both islands of New Zealand) numerous low scarps can be seen from the air and in aerial photographs; and commonly these are parts of "cicatrices", as they may be called, which mark the outcrops of long, continuous faults. Some of them trace nearly straight lines for 50 miles and more. Ongley[24, 25] has deciphered the long cicatrice (Fig. 311) of the main fault associated with the severe Wellington earthquake of 1855, and has also described in detail a scarplet formed in East Wellington in 1942. In Fig. 312 part of a scarplet is shown that may be traced for many miles parallel to the course of the Wairau River, New Zealand, and must be regarded as a fossil earthquake of the first magnitude.

It is recognised that discovery of faults that are sufficiently active to make their presence known by pushing up scarplets is of the utmost economic importance in selecting sites for dams,[20] and also for distinguishing those areas in which there is considerable earthquake risk. "A marked fault movement affecting the surface cannot be expected to occur without an accompanying strong earthquake"

Fig. 312. Scarplet (8 feet high) in the Wairau Valley, South Island of New Zealand. The Wairau River flows (left to right) between the pine trees and the dissected valley-side scarp in the background.

(LOUDERBACK),[20] and, as some scarplets afford evidence of a succession of small movements that have added to their height,[24] it is not unreasonable to expect that future movements will occur along the lines of some fault cicatrices.

Though "most earthquakes occur . . . at depths between five and 15 miles" (GUTENBERG), there are many recorded estimates of greater depth of origin, some exceeding 25 miles. Such great depths may seem to discredit the theory that earthquakes result from displacement on faults that extend to and dislocate the land surface. It is clearly the first movement, however, perhaps taking place at the greatest depth to which a fault crack extends, that generates the waves making the earlier and more significant part of the seismogram from which calculations of depth of origin are made. "The break", probably "starts from one point and is propagated along the fault plane with a velocity not exceeding the velocity of longitudinal waves" (GUTENBERG). In many instances it seems that the fault movement and dislocation extend thus to the earth's surface, and the earthquake is then felt severely in the vicinity of the fault trace or outcrop.

In the case of some earthquakes to which an exceptionally deep-seated origin has been assigned it has been suggested that some

V. C. Browne, photo

Fig. 313. View looking north-east along the Awatere fault scarp, South Island of New Zealand, showing a cicatrice along the fault line which is marked by a reverse scarplet, or "earthquake rent".

obscure disturbance probably involving "change of bulk" has taken place in material at a depth of perhaps hundreds of miles and has generated an earthquake such as will be recorded at distant stations, while it is also the cause of superficial faulting of the kind that produces scarplets and causes severe shaking in their vicinity.[23] According to Gutenberg and Richter,[13] however, the characteristics of "deep-focus" earthquakes are such as to indicate that their immediate cause is of the same nature as that of shocks of shallow origin, i.e. of ordinary earthquakes. If this conclusion is correct, even deep-focus earthquakes must be attributed to dislocation on faults, and the depth to which fracturing extends, especially in parts of the circum-Pacific belt, must be very much greater than has generally been supposed. Some, perhaps most or all, of the dislocations that make earthquakes of very deep origin fail to extend to the earth's surface, however.

The relation of some scarplets to fault fissures is indicated by the association of hot springs with them—for example, with those at Genoa, Nevada,[18] and some along the base of the Wasatch Range, Utah[11] (Fig. 307).

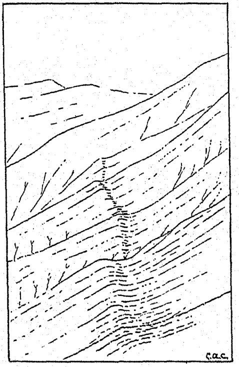


Fig. 314. Left: Reverse scarplet along the base of the Kaikoura Range in the Clarence Valley, New Zealand.
Right: View southward along the upper of two cicatrices, with reverse scarplets, on the eastern scarp of the Ruahine Range, New Zealand. (After Waghorn.)

Earthquake Rents or Reverse Scarplets

In New Zealand a considerable number of long cicatrices, or continuous scarplets, that have been described as "earthquake rents"[21] closely parallel the base-lines of scarped ranges in such a way as to make it quite obvious that they are related to major faults. It is commonly found, however, that in such cases the scarplets face the main scarps to which they are obviously related, enclosing shallow trenches between the scarps and scarplets (Fig. 313). These in some places remain open and contain standing water after rain, but in other places are partly filled with debris and so converted into benches of variable width. The *reverse* form indicates that the very recent movements that produced these scarplets, or rents, have been reversals of the main movement on the faults. This suggests that great fault movements are not only intermittent but are also sometimes reversed in direction. It is possible that reversal, or

retrograde movement, is especially characteristic of thrust faulting, which may give place to normal faulting on the same plane.

There appears to be no record of reverse-sloping scarplets outside New Zealand, with the exception of some which traverse only alluvial deposits in front of the Wasatch and Panamint Valley fault scarps[14a] and are perhaps caused by subsidence[2] or produced by local buckling on a strike-slip fault. In New Zealand many of these earthquake rents, or *reverse scarplets,* as they are perhaps better called, have been reported (Fig. 314). Some in the Hawke's Bay district have been described and well figured by Waghorn,[33] and some in the Alpine region of the South Island by Speight.[30] These reverse scarplets, like all known fault cicatrices in New Zealand, trace simple lines, some of them nearly straight for long distances. One, for example, along the north-west side of the Awatere Valley tectonic depression (Fig. 313), where it closely follows the line of a fault that is probably a high angle thrust, is clearly marked for nearly 60 miles. In no case do they follow the contour lines, but they ascend and descend across bedrock spurs (Figs. 313, 314) and are, therefore, not a result of local subsidence of alluvium, although they have been traced across fans also.[30]

Horizontal, or Transcurrent,* Displacement

Most tectonic earthquakes, as distinguished from tremors that are related to volcanic eruptions and are felt severely over a rather limited area, occur in regions of block faulting, and are directly caused by sudden movements on faults. Movements on the San Andreas fault, in California, such as resulted in the San Francisco earthquake of 1906, take place horizontally, however, along an approximately vertical plane of dislocation. The lines of such transcurrent faulting, or strike-slip movement, are markedly straight for long distances, showing that slipping on major planes of crustal dislocation is taking place. These faults do not generally upheave block mountains, though the terrain on one or perhaps both sides of the break buckles in places. There are other topographic complications to be expected however.

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* Nomenclature follows J. Geikie, *Structural and Field Geology*, esp. 5th ed., 1940, and E. M. Anderson, *The Dynamics of Faulting*, Edinburgh: Oliver and Boyd, 1942.

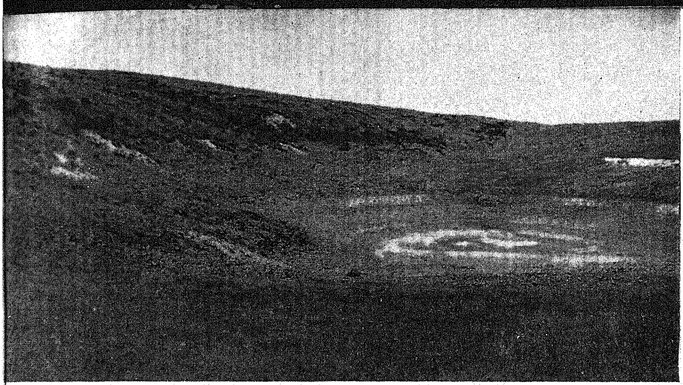

Fig. 314A. Sag pond on a part of the Hope fault, New Zealand, affected by transcurrent (strike-slip) movement and buckling of the surface.

A landscape pattern may be found simply dislocated by lateral shift to the extent of the sum of many small movements; but only the more recent of transcurrent movements are traceable in this way. Offsetting of small streams and their valleys to the extent of from 200 to 600 feet on the line of the Haywards fault, in California, has been described,[29] and features of other examples are mentioned by Buwalda,[2a] who employs the term "shutter ridges" for spurs shifted sideways so as to block ravines. In south-eastern California, where Noble[22] has described the fault-zone features of the San Andreas and Garlock faults in some detail, lateral displacement has taken place on so enormous a scale and has been so distributed through a belt, or fault zone, that matching of features that are disarticulated parts of single ridges or valleys on opposite sides of the belt has not been possible. In fact similar features are not present, and there are not even similar topographic patterns. In general both the geological formations and structures and the topographic patterns are entirely different on opposite sides, so great has been the aggregate displacement; and within the fault zones the shearing movement has broken the terrain into narrow but somewhat elongated fault blocks, or splinters.* Close to the

* For a photographic illustration showing these features see P. G. Worcester, *Geomorphology*, 1939 (Fig. 347).

lines of most recent dislocation there are also undrained hollows that contain small lakes, or "sag ponds" (compare Fig. 314A), due to buckling of the surface.

Buckling of the surface on one or perhaps both sides of a transcurrent fault, such as has taken place along the recently active segment of the Hope fault, in New Zealand,[3a] produces scarps or scarplets that face alternately in opposite directions; and purely horizontal movement, even without buckling, makes short local

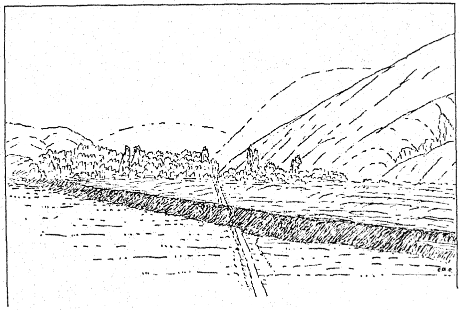

Fig. 315. The Mino Owari fault scarp, formed in Japan in 1891. (Drawn from a photograph.)

scarplets wherever the fault line crosses spurs or ridges, as was observed in California on the San Andreas line in 1906. The scarplets shown in Fig. 305 indicate some dextral (to the right) as well as vertical displacement.

Sudden Changes of Level

Transcurrent movement seems to be rather exceptional, and more usually the sudden jerks of movement on faults observed in association with earthquakes have been predominantly vertical displacements, though some of the faults may be gravity faults and others appear to be thrusts. The formation of scarplets in association with such movements has already been referred to. A spectacular development of a scarp across the lines of valleys—the first development of

Fig. 316. Wharf at Napier, New Zealand, raised 6 feet in 1931, as it appeared a year after the earthquake. Dark bands of marine growth clearly indicate the former and new high-water marks on the piles.

a new scarp to be observed and accurately recorded—took place in Japan in 1891[16] (Fig. 315).

The changes of level resulting from such upheavals produce the most striking results where they affect coastal areas. Very uniformly raised beaches emerged at Wellington, New Zealand, in 1855, and more irregular changes of level have since been recorded elsewhere —for example, at Yakutat Bay, Alaska, 1899,[32] and in the vicinity of Tokyo, 1923. In New Zealand, in 1931, uplift took place on the north-west side of a line running north-eastward to the coast just south of Napier.[14] Wharves rose 6 feet (Fig. 316), and thousands of acres of tidal mud-flats near Napier were converted into a plain that has since become cultivated land.

Effects such as those just described are not the results of earthquakes, but are produced by earthquake-making earth movements. The actual earthquake shaking brings down landslides, large and small, the scars of which must be distinguished from fault scarps. Small scarps also, generally short and curved, and perhaps grouped in networks, develop owing to settling and subsidence of unconsolidated material, the surface of which may be thrown into irregular ridges and mounds without direct relation to underlying faults. Funnel-shaped pits, like small craters, are also formed, where fountains of water are ejected from sand or gravel deposits that settle as a result of agitation. Such minor features are formed in abundance in the severely shaken areas close to centres of earthquake origin.

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CHAPTER XXII

Some Fault and Fault-line Features

FAULTING, BOTH RECENT AND ANCIENT, HAS FREQUENTLY BROUGHT together weak and resistant rocks on opposite sides of a fault surface, or, in terms of a map, a fault line, so that removal of the weak rocks from one side by erosion leaves exposed a scarp of the more resistant rocks on the other side, and this persists in the landscape until it is degraded by erosion and obliterated.

EROSIONAL FAULT-LINE SCARPS

A scarp thus developed by erosion along the line of a fault has been termed by Davis[13] a *fault-line scarp,* and this term is now well established in spite of the obvious defect of not being fully self-explanatory to the extent of making clear the vital distinction between fault scarps and fault-line scarps—i.e. between new-made tectonic forms and forms that may be due entirely to reawakened activity of very long delayed differential erosion. " 'Fault-line erosion scarp'* is less concise, but also less open to misinterpretation" (JOHNSON).[16] The difference has been overlooked by many authors —"fault" scarps have been defined as erosion-made[4]—but it is impossible to over-emphasise the importance of distinguishing with meticulous care between fault-line scarps and fault scarps, thus avoiding the possibility of introducing grave errors into interpretations of geological history from surface forms.

Being exposed by differential, or selective, erosion,

> fault-line scarps develop best in the mature or post-mature stages of the erosion cycle. They may be non-existent in the very youthful stage, and theoretically they should be effaced before the end of the cycle. . . . They are most prominently brought out in relief during that long intermediate stage in the cycle which has been reached over the greatest areas of the continents (BLACKWELDER).[3]

In contrast, therefore, with fault scarps, which appear only in seismic belts affected by contemporary earth movements, fault-line

* In later writing Johnson[16a] has dropped this suggestion of a change in nomenclature.

scarps are found the world over, being almost as widespread in their occurrence as the processes of differential erosion that produce them. In most parts of the world fault-line scarps have been developed as a result of a recent stimulation of erosion by a regional uplift dating long after the formation of the faults, and long after

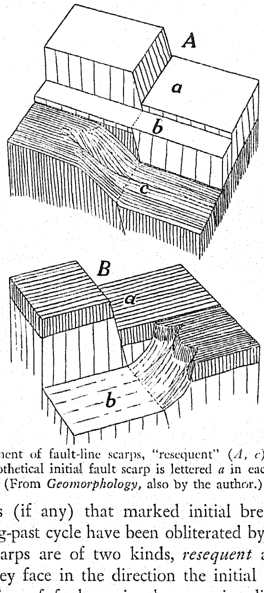


Fig. 317. Development of fault-line scarps, "resequent" (*A, c*) and obsequent (*B, b*); a hypothetical initial fault scarp is lettered *a* in each diagram. (From *Geomorphology,* also by the author.)

the fault scarps (if any) that marked initial breaks of the land surface in a long-past cycle have been obliterated by ancient erosion.

Fault-line scarps are of two kinds, *resequent* and *obsequent,*[13] according as they face in the direction the initial fault-scarp faced on the same line of fault or in the opposite direction. Thus a resequent* scarp faces, or descends towards the structurally

* With some show of reason King[18] prefers to describe most so-called resequent fault-line scarps as "consequent". They are consequent, that is, if at no stage during their erosional development have scarps facing in the direction opposite to that of the original (consequent) fault scarps on the same lines been temporarily in existence.

depressed (downthrown) side of the fault (Fig. 317, *A, c*), and an obsequent scarp towards the structurally uplifted (upthrown) side (*B, b*). Resequent fault-line scarps are commoner than obsequent, since it is true in a general way that the more deeply buried rocks, being older and having been subjected to greater pressure than those overlying them, are harder and more resistant to erosion. Exceptions to this rule are quite common in flat-lying sedimentary series where limestones and sandstones are more resistant than other formations (shales, for example) on which they may rest, as also

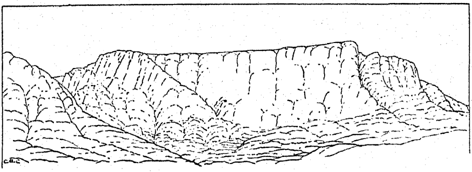


Fig. 318. Table Mountain, Capetown, bordered by escarpments perhaps developed from fault-line scarps.

are lavas and intrusive sills; or older and more indurated rocks may overlie younger and softer rocks as a result of earth movements of overthrusting, as is the case along the eastern front of the northern Rocky Mountains. An example of a thick resistant formation extensively overlying weaker rocks is the Table Mountain sandstone of South Africa, and the escarpments around Table Mountain, at Cape Town, might be interpreted as obsequent fault-line scarps around a downfaulted (or perhaps downwarped) portion of the sandstone stratum (Fig. 318).

A condition that leads readily to the development of an obsequent fault-line scarp from an ordinary ("consequent") fault scarp in a single cycle is the presence of a superficial sheet of lava lying on weaker materials before the fault movement takes place (Fig. 317, *B*). After the formation of the initial fault scarp, the lava on the upthrown block, being weakened by the presence of softer rock (exposed in the scarp) beneath it, is liable to be destroyed rapidly by erosion, but the lava on the downthrown side may survive much

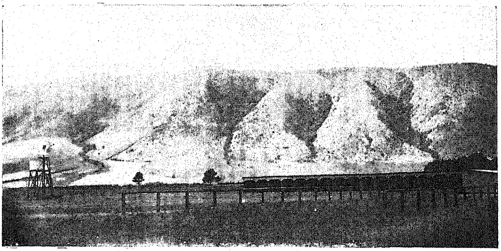
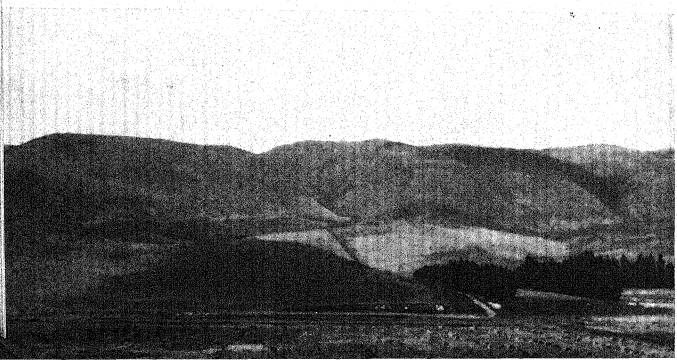


Fig. 319. A little-dissected one-cycle fault-line scarp (or possibly composite fault scarp) at Waimate, New Zealand (the eastern face of the tectonic block forming the Hunter's Hills range).

longer, its edge forming a fault-line scarp. Development of a resequent (or consequent) fault-line scarp in a single cycle is also obviously possible, and undoubtedly has very frequently taken place (Figs. 319, 320), but the introduction of the middle strip *b* in

Fig. 320. Little-dissected fault-line scarp (or possibly composite fault scarp) at Cave, South Canterbury, New Zealand, which is most probably of one-cycle origin. Structure as shown in Fig. 323.



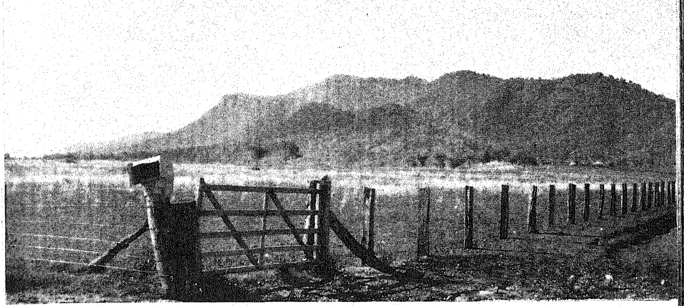


Fig. 321. West base of the Baldwin Range, New South Wales, which, as described by Professor W. N. Benson, is a fault-line scarp exposed by removal of soft mudstone of late Upper Devonian age along a fault contact with early Upper Devonian beds of resistant agglomerate. Relief, 1000 feet.

Fig. 317, *A*, representing the surface at the end of a cycle introduced by the fault movement, makes the diagram fit the case of a great number of fault-line scarps in stable crustal regions, where vast periods of erosion, broken by uplifts of a regional character, have intervened between stages *a* and *c*. The scarp in New South Wales which is shown in Fig. 321 serves as an example. A peneplain developed in such an intermediate cycle on soft rocks, so as to obliterate the last vestiges of the initial scarp (Fig. 317, *A, b*), has been locally preserved in a well-known instance beneath a lava flow spread across the trace of the fault, where preservation of a mesa-like promontory of lava-capped shale on the downthrown side of a portion of the long scarp in Arizona known as the Hurricane Ledge (Fig. 322) proves this portion to be a fault-line scarp.[12]

Where a fault-line scarp is exposed owing to rapid removal of very soft material in an early stage of its emergence, it may exhibit an almost continuous wall-like form, and the later dissection and degradation of this may simulate the stages of young and mature dissection of a fault scarp. Relative steepness of spur-ends, which may for a time even assume the form of facets, does not, therefore, serve to distinguish fault-line scarps from fault scarps.

Some fault-line scarps that have been identified by critical study are as high and as abrupt as most true fault scarps. The only necessary condition is an unusually massive and resistant formation

exposed to erosion along a fault contact with a very easily eroded formation. The latter may be reduced to a plain before the former has lost the aspect of youth (Blackwelder).[3]

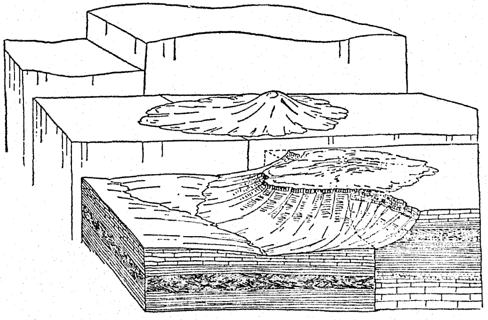


Fig. 322. Erosional ("fault-line") character of the scarp of the Hurricane fault, in Arizona, demonstrated by local preservation beneath lava of weak beds elsewhere removed by differential erosion from the downthrown side of the fault. (After Davis.)

Composite Fault Scarps

In the mobile belts, i.e. in the disturbed regions in which fault scarps are found, many tectonic scarps show fault-scarp relief combined with erosional fault-line relief. The combination, which is a true fault scarp above but a fault-line scarp towards its base, has been termed a *composite* fault scarp (Fig. 323).[7] It must be of common occurrence in any recently deformed block-faulted region in which a thin cover of weak strata lies upon a resistant undermass.

One of the scarps that break the even continuity of the westward slope of the Sierra Nevada of California, that at the debouchure of the Kern River from the mountains, dislocates such a cover and undermass. It has been diagnosed by Blackwelder[3] as a fault-line scarp; but Gilbert,[14] who has described the fault on this line rather than the scarp, has left open the question whether the latter is in part a true fault scarp, while recognising that it has been in part exposed

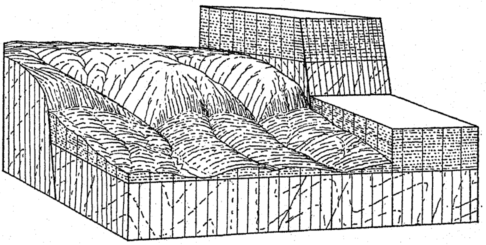


Fig. 323. Development of a composite fault scarp.
(From *Geomorphology,* also by the author.)

by erosion. Blackwelder[3] estimates the maximum displacement on the fault as three or four thousand feet. If the thickness of the Miocene covering beds has been less than the throw of the fault in this locality, then, in so far as erosion has spared the original fault scarp, part of the existing feature must be a composite fault scarp.

Composite scarps force themselves on the attention of observers in New Zealand. On a terrain with compound structure fault scarps

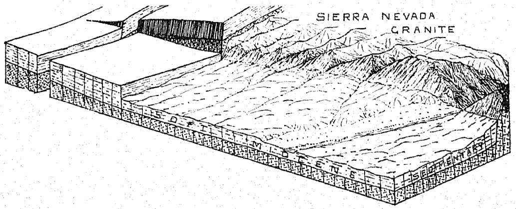


Fig. 324. Development of the composite (or wholly fault-line?) scarp at the debouchure of the Kern River from the Sierra Nevada of California. Compare photographs by W. C. Mendenhall reproduced by Gilbert[14] and by N. E. A. Hinds (*Geomorphology,* 1943, p. 178).

may degenerate into fault-line scarps early in the course of a first postfaulting cycle, and will do so if the cover is easily eroded and if the vertical displacement on the fault is of smaller measure than the thickness of the cover. Fault-line scarps so developed clearly do not cease to be tectonic forms. Where, as in much of the southern part of New Zealand, the thickness of the cover is considerably less than the displacements on the major faults, erosion even to the stage of late maturity does not wholly destroy the true fault scarps, though removal of the weak cover from downthrown blocks frequently exposes fault-line scarps below the base lines of the fault scarps. In such a case the scarp as a whole, as it exists at the present day, is composite. The lower part of a composite fault scarp (Fig. 323), having been recently stripped, may be expected to retain something of the wall-like form of the fault surface, or to display blunt or faceted spur-ends resembling those of a young or rejuvenated fault scarp. Tectonic fault-line and composite scarps form wall-like boundaries of blocks in the Lower Waitaki graben complex (New Zealand), as shown in Figs. 287 and 288 and referred to in Chapter XX. If removal of the cover has been somewhat long delayed, blunt or faceted spur-ends may persist after the fault scarp above has been so thoroughly dissected that its spurs, if they were not thus extended downward, would taper to points.

Composite fault scarps, fault-line scarps, and similar erosion scarps developed on monoclinal flexures have often hogbacks of resistant strata close to and parallel with their fronts. These are developed on the outcropping edges of beds formerly horizontal, and commonly members of the covering strata (if the structure is compound), which have been uptilted by the drag of the uplift of fault blocks or upheaval of anticlines (Figs. 278, 325, 325A).

In another kind of scarp combination, which Johnson[16] has referred to as composite, though not in the sense defined above, a fault-line scarp has been freshened by the development of a new fault scarp along its base as a result of posthumous movement on the ancient surface of dislocation. An example cited is "that part of the Hurricane Ledge just south of the Virgin River in Arizona."[16] As there is evidence of some posthumous movement on the great Alpine fault of the South Island of New Zealand[20] (p. 431), parts of the scarp along its line must be placed in this category.

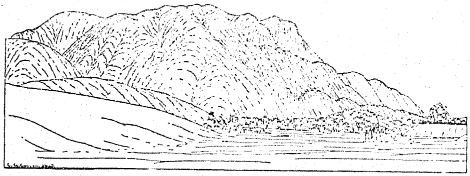
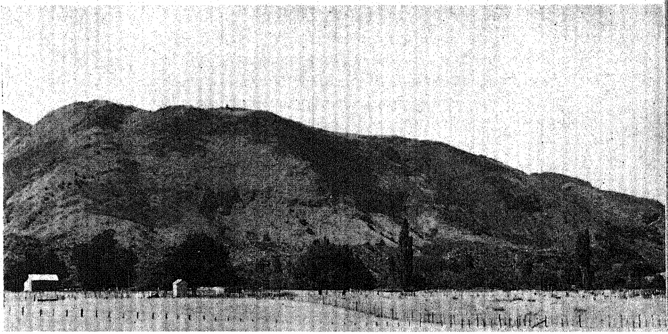


Fig. 325. Prominent high scarp at Takaka, New Zealand, with a hogback along the base on the outcrop of a limestone stratum of the cover upturned by drag close to the scarp, as in Fig. 278. (Compare Fig. 325A.)

According to Dixey,[13a] some though not all of the fresh fault scarps of eastern Africa have been developed by posthumous movement along very ancient lines of dislocation marked by the presence of fault-line scarps. He has come to the conclusion, indeed, that some scarps bounding so-called rift valleys in that region are simple fault-line scarps; while some others are features developed by differential erosion without relation to faults ancient or modern. Other geologists, however, see evidence of very recent faulting on a magnificent scale.

Fig. 325A. Part of the scarp with hogback along the base shown in Fig. 325.



Resurrected Scarps

Yet another variety of scarp to some extent resembling the consequent or resequent variety of fault-line scarp, but not to be confused with it, is the *resurrected fault scarp.*[16] In general, resurrected fault scarps are those that have been re-exposed by erosion long after having been buried, while fresh, beneath the bahada deposits which accumulate along block fronts in cases where the debris of their destruction is not removed by rivers. The "impressive escarpment" west of Clermont-Ferrand, in the Central Plateau of France, has

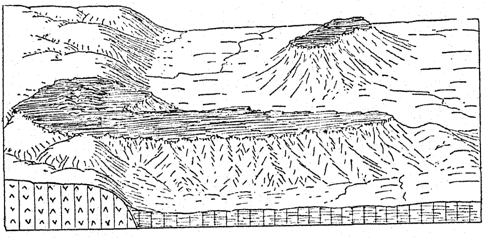


Fig. 326. The resurrected fault scarp at the Montagne de la Serre, near Clermont-Ferrand. (After a drawing by W. M. Davis.)

been selected by Johnson[16] as the type of resurrected fault scarps (Fig. 326). As in the case of the fault-line scarp of the Hurricane Ledge a lava flow that crossed the fault line at a time when it had no expression as a surface feature has preserved in the form of a promontory (Montagne de la Serre) a considerable remnant of the weak superficial formations that elsewhere have been removed from the low side of the scarp, but in this case the weak materials consist of alluvium that accumulated in front of and during the growth of an ancient (Oligocene) fault. Resurrected fault-line scarps also are known; and the scarp at the base of which flows the Wairoa River, near Auckland, New Zealand, has been so described by Bartrum[1] (Fig. 327). In central France a resurrected graben is recognised.[16]

Professor J. A. Bartrum, photo

Fig. 327. The Wairoa scarp, Auckland, New Zealand. After development by erosion as a fault-line scarp this has been almost completely buried under alluvium (which forms low hills opposite the scarp) and has been later resurrected by revived erosion. The resurrected part of the scarp is the strip below a well-marked shoulder.

Fault Valleys and Fault-line Valleys

Structural grabens excavated between fault-line scarps by differential erosion to become lowlands again are of common occurrence as broad landscape features—for example, the Scottish lowland. Many valleys also are opened and enlarged by headward erosion along single fault lines, or rather along the belts of shattered and very much weakened rocks that are developed to a considerable width along the surfaces of displacement of great faults when, as is sometimes the case, the fault is not a clean break but is "distributed". Such valleys, being wholly produced by erosion, and in many cases in cycles later than the obliteration by ancient erosion of any consequent features on the same lines, are *fault-line valleys*[13] in the strict sense of the term. There is no such thing as a true "fault" valley in the sense of a gaping fissure that guides consequent drainage, at any rate on such a scale as to make it of any importance; but consequent rivers that are guided by fault-angle depressions are "fault" features rather than "fault-line" features, even though they

may have excavated inner valleys along or parallel to the fault lines. A true fault valley of another kind may be made as a result of reversal of fault movement such as will upheave a new fault scarp that will face an earlier-formed fault scarp, the two enclosing the fault valley between them (Fig. 327A, left). It is quite possible that the Hope River valley, in the South Island of New Zealand, which is on the line of an active fault, originated in this way.[10a] In more stable regions, on the other hand, the majority of the valleys that are obviously guided by faults are erosional fault-line features (Fig. 327A, right).

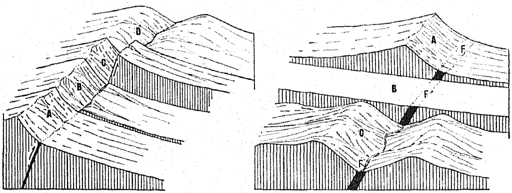


Fig. 327A. Left: Stages of development, A, B, C, D, of a fault valley by faulting in reverse. Right: Stages of development A, B, C, of a fault-line valley on a fault zone F.

Fault-line valleys have been termed *resequent* and *subsequent* by Davis[13] according as they do or do not follow lines of former consequents related to the same faults, but as it is generally impossible to come to a decision on this point, the distinction is of little practical value.

Collinear fault-line valleys make a remarkably straight erosional depression transecting the Highlands of Scotland for 100 miles from south-west to north-east as the Great Glen, which is followed by the Caledonian Canal. It has been eroded along a belt of crushed and metamorphosed rocks a mile wide, which were weakened by ancient shearing on a transcurrent fault with lateral displacement estimated at 65 miles.[17] In New Zealand the most remarkable earth lineament that has been recognised is a somewhat similar belt of linear eroded depressions that extends for more than 200 miles

along the west coast of the South Island, backed by a nearly continuous straight fault-line scarp on the line of the ancient Alpine fault, the western front of the folded welt of the Southern Alps and boundary between its schist zone and foreland[10, 20] (Fig. 328).

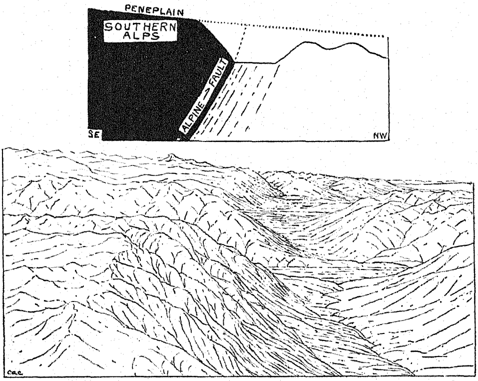


Fig. 328. View (with key diagram) along valleys aligned on the Alpine fault in Westland, New Zealand. The large transverse valley in the middle distance is that of the Grey River. Above the fault-line scarp (4000 feet high) at the Alpine fault is (at left) an up-arched peneplain, the initial form of the main range of the Southern Alps as it exists to-day. In the distance this is seen on both sides of the fault line. From an aerial photograph by Allan Prichard.

The stream pattern of central Sweden results from the circumstance that the streams have been developed by headward erosion on an ancient rectangular or rhomboidal fault network (Fig. 329). A neat example of an isolated fault-line valley is that occupied by a short reach of the Kaiwarra stream, Wellington, New Zealand (Fig. 87), where rapid headward erosion along a fault line has resulted in capture of a stream that had earlier taken its course along an adjacent segment of the fault line.

With the object of distinguishing where necessary between such features and consequent valleys in narrow grabens (some "rift valleys") Johnson[16] has deduced the forms of graben-like valleys that may be developed by a combination of fault-line erosion and renewed faulting along single faults. Such a valley may be enclosed between an obsequent fault-line scarp and a fault scarp (Fig. 330). A form similar in a general way, though not symmetrical as regards the height of the enclosing scarps, may be produced simply by

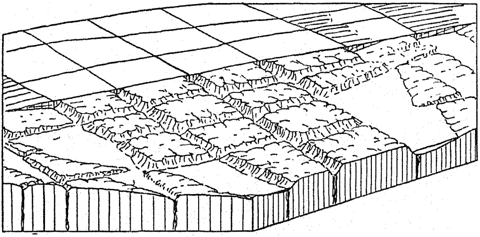


Fig. 329. Fault-line valleys of central Sweden. (After Davis.) After "a broad uplift without faulting, and in the cycle of erosion thus introduced and still current, many narrow fault-line valleys have been eroded along the shattered zone of the faults in the area of the resistant crystallines, and broad lowlands have been excavated, partly by aid of glacial erosion, in the large patches of covering strata" (Davis).

erosion in a single cycle from the initial form in Fig. 330. Such a fault-line valley, enclosed between a composite fault scarp and an obsequent fault-line scarp, is shown in Fig. 271, separating the Truxton mesa from the Arizona plateau.

Fault Splinters

Intermediate in character between faults that are clean breaks and those that are distributed through a fault zone or shatter belt of crushed rock are *step faults* and *splintered faults*.[12] In the former the dislocated land surface, or that revealed by erosion in the case of fault-line scarps, descends in a step-like series of low scarps, which in some large-scale examples remain separate, but which, if small

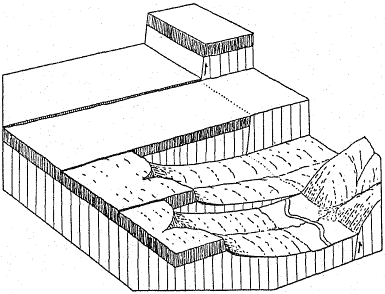


Fig. 330. Successive stages in the development of an "obsequent-consequent" pseudo-graben valley.

and numerous, tend to merge into a single scarp as degradation proceeds,[19] though even at a stage of maturity of dissection of the compound scarp they may be traced as jogs in the crestlines of the spurs that descend from the face of a block mountain. In the case of a splintered fault, while the displacement on the whole fault system remains reasonably constant, dwindling displacement on

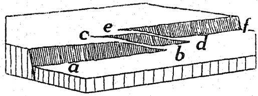


Fig. 331. A splintered fault dislocating a plane surface. (From *Geomorphology,* also by the author.)

one line (such as *ab,* Fig. 331) is compensated by the development parallel to it of another line of fault (*cd*) with increasing displacement, and this may occur more than once (*ef*); so that discontinuous faults *en échelon* separating successive splinters form the complex boundary between adjacent relatively upthrown and downthrown blocks. It is as though faulting had followed pre-existing lines of weakness—lines of least resistance—running diagonally across the boundary between two tectonic blocks.

Both fault scarps and fault-line scarps may exhibit splintered features. They are common on the young fault scarps of southern Oregon (Figs. 282, 332). Fig. 333 is a copy of Davis's drawing of the great splinter of the Hurricane fault in southern Utah.[12] Several very well defined splinters diversify the line of the composite scarp

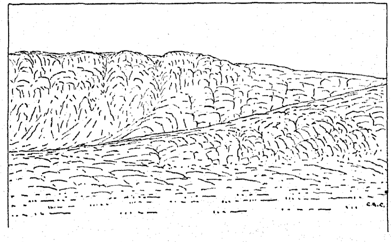


Fig. 332. Splinter, or "inclined step-fault block" (FULLER), on the young fault scarp of Northern Steens Mountain, Oregon. (Drawn from a photograph.)

separating the resurrected fossil plain (or peneplain) of South Canterbury, New Zealand, from the graben occupied by the valley of the Waitaki River.[8] That figured (Fig. 334) forms a broad ramp, or gangway, descending 1000 feet from the upland plateau, with which it is continuous at one end. In Central Otago two splinters with the dimensions of subsidiary fault blocks descend ramp-like from the scarp of Rough Ridge[9] (Fig. 335).

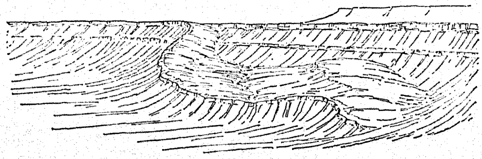


Fig. 333. Rock splinter on the Hurricane fault. (After Davis.)

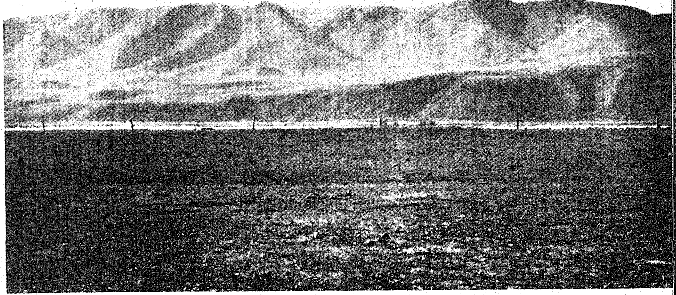


Fig. 334. Splinter of the scarp forming the north wall of the lower Waitaki Valley graben, New Zealand.

Diagnosis of Fault Features

So important is it to distinguish true fault scarps, together with composite features of a first postfaulting cycle, from those resulting from differential erosion in a later cycle that it would be desirable, if it were possible, to set out clear-cut rules for their differentiation in the field. In practice, however, difficulties arise. Some criteria that have been relied on are merely proofs of the presence of faults so closely parallel to scarps as to have obviously some causal relationship to them, but the distinction between fault scarps and

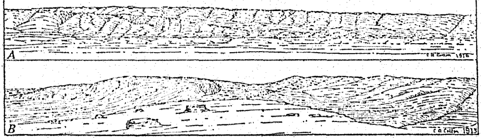


Fig. 335. Two views of the splintered scarp of Rough Ridge, New Zealand. *A*, view looking north-west; *B*, view looking south-west along the splinter shown in view *A*.

fault-line scarps remains to be made. The most easily applied test is the purely artificial and unscientific one that in many large regions, indeed in all parts of the world except certain definitely limited regions, no true fault scarps have ever been reliably identified. The testimony of Johnson on this point has been quoted in Chapter XX; Baulig[2] also has remarked: "I know of no feature in the whole of France that can be confidently accepted as a true fault scarp." This excludes resurrected features, of course, which may survive from very ancient times.

It is in seismic regions, in the "mobile belts", that the question of fault-scarp identification arises. Here the isolation of fault scarps may have to be tackled in two stages. Scarps related to faults must first be distinguished from other features more or less resembling them, and then tests may be applied to prove or disprove first-cycle character, and so to determine whether the features of the landscape are largely or at least in part tectonic or are due entirely to differential erosion.

The commonest of the landscape forms from which features related to faults and fault-lines must be distinguished are: (1) valley sides cut back to lines of bluffs by lateral stream corrasion; (2) trough walls straightened and steepened by glacial erosion; (3) lines of sea cliffs formed where marine erosion is cutting back a coast; (4) steep mountain fronts that are receding as a result of long-continued erosion under arid conditions; and (5) structural escarpments.

Except in the unusual case of undissected scarps of equal height facing each other across a narrow graben, the distinction from (1) and (2) is easily made. Only in very exceptional cases do fault scarps occur in matched pairs, and in the very common case of a fault-angle depression that may become a river valley, the cross-section is highly asymmetrical. In the case of the Hutt River valley, New Zealand,[6] this asymmetry is seen in Figs. 298 and 335A, both of which show a fault scarp forming a straight wall on the north-west side, while the opposite valley-side is embayed, with extensions of the alluviated valley-floor in the embayments (see also Figs. 255, 340).

A useful point of distinction from a wave-cut coast is the absence at the base of a fault-scarp facet of a recognisable broad abraded rock platform, which would preserve the plan of a former

Photo from Public Works Department

Fig. 335A. View looking north-east up the Hutt Valley, New Zealand, showing the fault-angle form. (Compare Fig. 298.)

coastal salient cut back by marine erosion and would be cut in rocks of the same kind as those exposed in the cliffs. A strip of plain found in front of the base of a fault scarp would, on the other hand, be a bahada underlain by the waste resulting from degradation of the scarp, or, in the case of a young fault scarp descending into the sea, there would be at first, as a rule, deep water close to the shore, and in early sequential stages an apron of marine sediments separated from the cliff base by a *narrow* strip of marine-cut platform. Along the base of the Wellington fault scarp, for example, which descends to the north-west shoreline of Port Nicholson, New Zealand (Fig. 336), absence of outlying reefs and the presence of deep water close to the cliff base are good indications of the occurrence of recent fault movement.[5] In the case of marine erosion developing a fault-line scarp, outlying reefs cut down by wave action would consist of rocks distinctly different from and weaker than those in the scarp; but a shoreline of submergence

localised on either a young fault scarp or a fault-line scarp, as described by Johnson,[15] would resemble a fault scarp descending initially into the sea.

In front of a scarp of desert erosion there is a complementary rock-cut sloping plain, or pediment, veneered only thinly with discontinuous alluvial gravels, whereas a young fault scarp under similar conditions of climate has at its base only a narrow bahada, and this, together with any alluvial or lake-formed plain in front of it, may be underlain by alluvial deposits to a great depth, as has been indicated in some cases by well-drilling.[3]

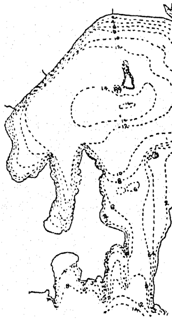


Fig. 336. Depth contour map of Port Nicholson, N.Z. (contour interval, 2 fathoms). Deep water is present along the north-west straight shoreline, which is the line of the Wellington fault.

As regards the distinction of fault scarps from structural escarpments, a fault scarp can, of course, be formed in rock formations the structure of which favours the development of escarpments, and fault-line scarps also can originate in strata with such structure suitably faulted. Thus many fault scarps and fault-line scarps, as they are worn back by erosion from the faults, are also escarpments. The distinction of such scarps from simple escarpments does not generally present difficulties, however, for in stratified rock formations with escarpment-making structure the presence or absence of great faults is generally obvious. In contrast with the necessary

parallel relation of rock strike and outcrop to scarp trend in structural escarpments, there is obviously no necessary correspondence between the strike of strata or fold axes and the trends of scarps—especially true fault scarps—related to the lines of faults. Thus the outcrops of inclined or folded strata commonly run obliquely up and down scarp faces, as Davis realised when he first deduced the diagnostic features of scarps produced by major

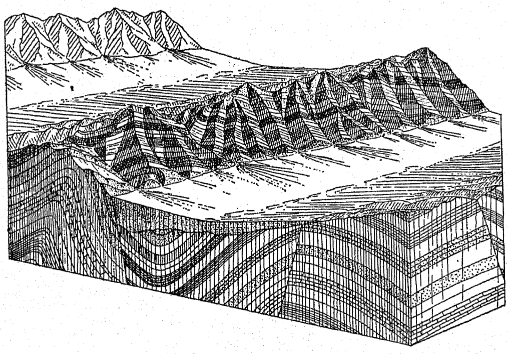


Fig. 337. Deductively imagined features of a dissected high fault scarp forming the boundary between a range and a basin of tectonic origin in a terrain of old, deformed stratified rocks. (After W. M. Davis, *Science*, 14, 1901.)

faulting,[11] and designed the block diagram here reproduced as Fig. 337. Fault scarps that face Death Valley, California, afford good illustrations of such diagonally outcropping strata (Fig. 338).

Criteria of Recent Faulting

Some special features of fault scarps that may be relied on, where they are developed, to make a distinction from fault-line scarps have been listed by Blackwelder.[8] Among these the following may be noted:

(1) "Poor correlation between rock resistance and surface form" contrasting with "close" correlation in the case of fault-line scarps.

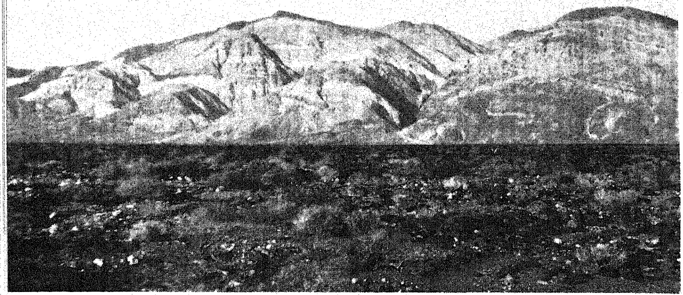


Fig. 338. A fault scarp facing Death Valley, California, which shows structural bands of outcrop running down the scarp diagonally. (Compare Fig. 337.)

Definitely development of a fault-line scarp depends on a strong contrast in the resistance offered to erosion by rocks on one side of the fault as compared with those on the other.

(2) Alluvial deposits (if present) on the downthrown block thickest near the fault line.

(3) Lake, or "sink", close to the scarp base.

(4) Alluvial fans abnormally small (Figs. 294, 297).

Criteria (2), (3), and (4) are not usually applicable in humid regions, where throughgoing rivers of considerable size in the depressed areas of a fault mosaic may either carry away all the detritus resulting from fault-scarp degradation or redistribute it in such a way as to mask deep basin-plain filling. So also one of Blackwelder's indicators of fault-line scarps, "little or no alluvial deposit on the downthrown block", is of no diagnostic value for them in humid regions. He remarks, moreover, that "a sheet of alluvial materials 200 feet to 400 feet thick may be the result of a mere climatic change".

(5) Frequent severe earthquakes. These indicate that "movement is actively going on; and it is only such relatively frequent dislocations that outstrip the erosional processes and produce notable fault scarps".

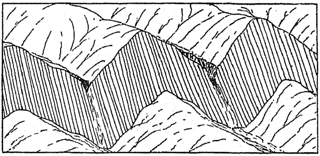


Fig. 339. Ideal evidence of landscape faulting. An infantile fault scarp intersecting a maturely dissected land surface.
(From *Geomorphology*, also by the author.)

(6) Basal scarplets. Association of the emergence of these with earthquakes is well known.

(7) Displacement of an older topographic surface. It is almost too optimistic to hope to find a landscape surface dislocated by faulting but in such a state of preservation that the parts below and above the fault may be neatly fitted together again, as pictured by Davis[13] in a sketch of imaginary "young faults in a mountainous district", or as roughly shown in Fig. 339. Remnants or traces of a prefaulting surface thus dislocated may sometimes, however, be

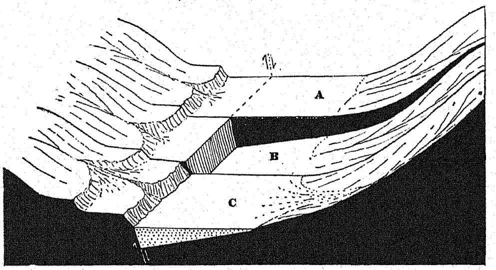


Fig. 340. Imperfect matching of forms in a landscape dislocated by faulting. Such contrast between valley-sides divorced by recent faulting is found in the Waiau-Hanmer basin plain and in the Hutt Valley, New Zealand. A: Form of the valley prior to the latest faulting; B: initial postfaulting form; C: sequential form after some alluviation of the valley has taken place.

tentatively correlated. Too often the land surface of a downthrown block has been deeply buried under extensive bahada or basin-plain deposits; or it may have been ruthlessly and rapidly cut to pieces by river corrasion. In the Hutt Valley, New Zealand, however, situated in a fault angle (Fig. 335A), a reasonable degree of matching is found on opposite sides (compare Fig. 340), when it is kept in mind that much alluvium has accumulated in the fault angle so as to hide the foot of the scarp, and also that the forms to be matched are, in addition to being thus separated by the alluvial plain now forming the valley floor, those of opposite sides of a prefaulting valley, for there was a valley already in existence on this line before the present fault-angle depression was formed.

Positive evidence of an entirely different kind may be available which leads to the diagnosis of a particular scarp as a fault-line erosional feature. It may be that some exceptional cause has locally led (as in the case of the Hurricane Ledge example, referred to earlier in this chapter) to preservation up to a high level of uneroded rock formations that have elsewhere been stripped away to expose the scarp. Definitely proved occurrence of superposed drainage across the scarped area is equally decisive. Of this Blackwelder has cited examples.[3]

Offsetting by Horizontal Heave

Lest horizontal offsetting of the outcrops of inclined strata, and of homoclinal relief features developed on some of these, where they are intersected by faults should be mistakenly accepted as a proof of the occurrence of transcurrent (strike-slip) movement along the faults, it is well to bear in mind that such offsetting results commonly from a simple erosional adjustment to structure accompanied by homoclinal shifting, which has taken place during the reduction of corresponding surface features to a common level on opposite sides of a fault. Small fault-line scarps are developed on the dislocated ends of strata left standing in relief as homoclinal ridges by differential erosion during this process, stages in the development of which are shown in Fig. 341, *A*. This diagram shows also how faulting followed by erosional lowering of the land surface may lead in some cases to suppression and in others to repetition of outcrops or strike ridges when faulting takes place on lines parallel to the strike (*B, C*).

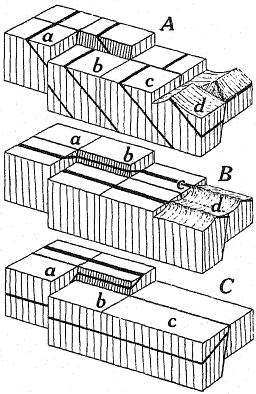


Fig. 341. (A) Offsetting of a homoclinal structure and ridge by faulting followed by erosion. (B) duplication and (C) suppression of the outcrop of a ridge-making stratum by faulting followed by erosion.

(From *Geomorphology,* also by the author.)

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CHAPTER XXIII

Limestone Landscapes

Although chemical weathering is accompanied by the removal in solution of some of the products of decay from most wasting land surfaces, during young and early mature stages of the geomorphic cycle mechanical erosion (corrasion) is so active that it overshadows chemical erosion (corrosion), and only when old age approaches is more than an almost negligible proportion of the total lowering of a land surface to be ascribed to this process, except in terrains of soluble rocks. In these, however, the effects of corrosion by solution assume importance in earlier stages of the cycle also, and in some regions the normal cycle of erosion is even superseded at maturity by a special "limestone" cycle. Limestone and the closely related dolomite and magnesian limestone are the only soluble rocks that occur commonly in sufficiently large masses to produce important landscape effects.

Lapies and Karrenfeld

Well-drained upland surfaces of limestone are often completely bare of soil, and the effects of solution by rain water are visible in remarkable small-scale relief forms of the bare-rock surfaces of such "limestone deserts". Among these are deep flutings (*lapiés*),[7] due to development of parallel furrows by solution where rain water runs down steep rock faces (Figs. 342, 343). (Such flutings, though rare, are not unknown on rocks other than limestone, e.g. being seen on basalt undergoing chemical weathering in Hawaii.)[19] A miniature mature landscape of close-set ridges separated by vertical-sided furrows several feet deep (*karrenfeld*) may develop (Fig. 344). A somewhat similar irregular rock surface is formed where limestone or other soluble rock undergoes weathering under a thin cover either of other strata[21] or of residual soil, and it has been suggested that all karrenfelds are such surfaces stripped of soil in recent times, perhaps after deforestation of the land,[10, 11] but Cvijić[7] maintains that most karren features are developed on outcrops of

Fig. 342. Karrenfeld showing lapiés on the Pikikiruna Range, New Zealand.

naked rock. They occur under jungle vegetation on the limestone surfaces of raised coral reefs on Pacific islands—for example, forming the "makatea" of Mangaia, described as follows:

The surface is formed entirely of hard splintery limestone projecting everywhere in sharp serrated pinnacles 10 to 15 feet in height, and is trenched by numerous crevices with vertical or even overhanging sides, many of them expanding into caves of irregular form and extent. The whole makatea structure is riddled with chasms, while vertical pinnacles and palisades with needle-like projections and razor edges are found everywhere in extravagant profusion. An intricate rocky maze is covered with a tangle of interlacing vegetation, making a surface almost impossible to traverse. (MARSHALL.)[16]

It is improbable that such karrenfelds (of the makatea type) have been recently stripped of a soil cover.

Whether it be true or not that lapiés are formed for the most part under a covering of soil, forms differing from those of a typical karrenfeld are developed on some outcrops of bare limestone. Daneš[9] has remarked upon the convexly rounded form of a conspicuous limestone summit, the Lion's Head, at Chillagoe, Queensland, attributing it to river erosion; but in New Zealand it is obvious

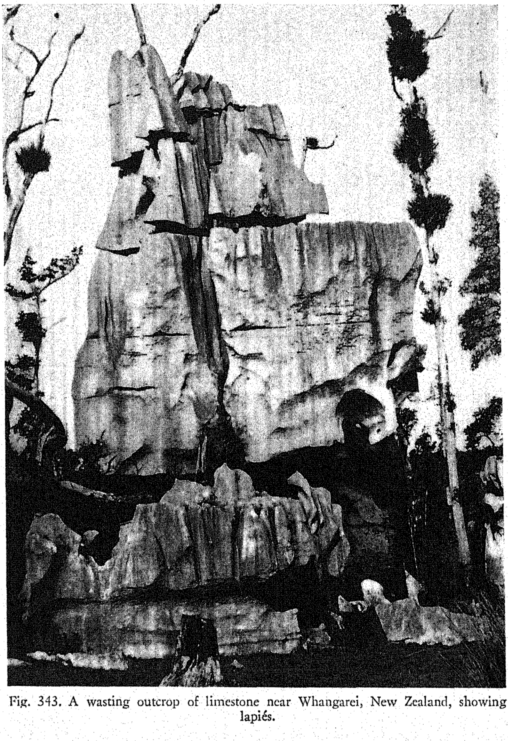
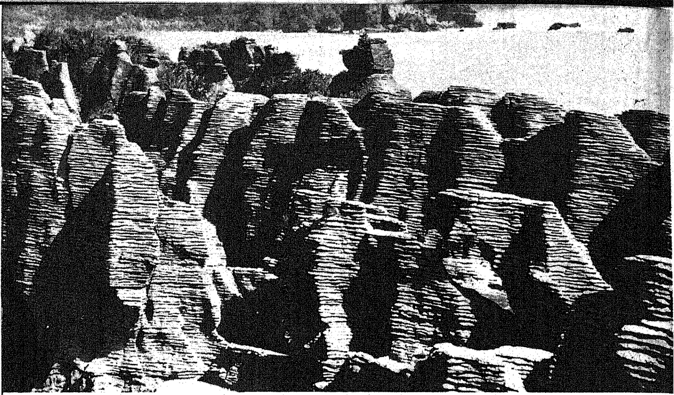


Fig. 343. A wasting outcrop of limestone near Whangarei, New Zealand, showing lapiés.



M. C. Lysons, photo

Fig. 344. Karrenfeld at Punakaikai, West Coast, New Zealand.

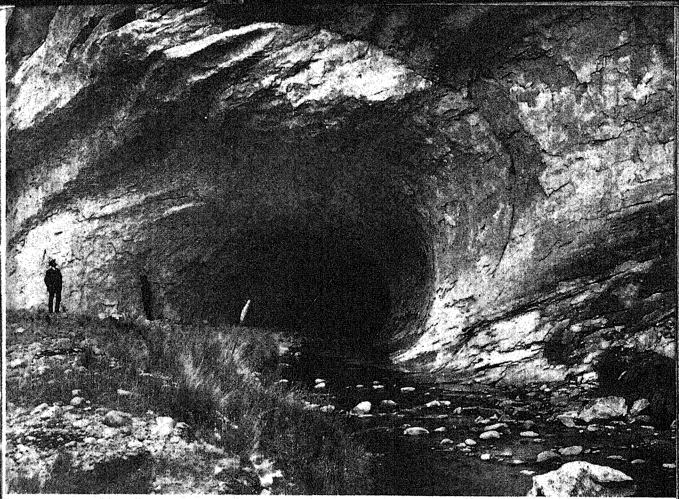
that some similar convex rounding of limestone outcrops results from exfoliation (Fig. 345).

Sculpture by development of closely-set vertical-walled potholes has also been found on limestone surfaces, as Zotov[28] has described. These have been formed rapidly by rain-water solution localised by growth of patches of a species of moss (Fig. 346).

Karst Landscape Forms

The development of a karrenfeld is taken by some authors as sufficient to characterise a landscape as a *karst,* but a karst landscape properly so called is an assemblage of larger-scale forms peculiar to limestone terrains. The word is of Jugoslav origin.[9] In particular the designation "holokarst" has been employed for the highly specialised landscape developed in Dalmatia on a thick body of limestone that extends down below sea-level.[8]

Solution underground, which results in the enlargement of fissures, followed by the swallowing through these of all surface water, is responsible for the development of the peculiar features of limestone or karst landscapes. When fissures are so enlarged that they become open passages or strings of caverns, they offer infinitely less resistance to the flow of water through them than do the minute passages between the grains, or the narrow joint crevices, in other

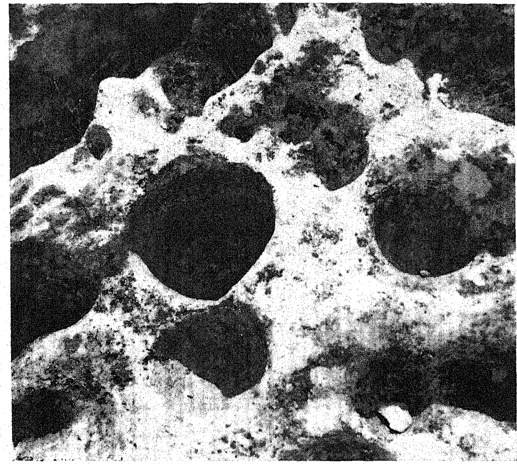


Professor R. Speight, photo

Fig. 345. Limestone surface rounded by exfoliation at the entrance to a cavern, Broken River Basin, New Zealand.

rocks; and so there is little or no heaping of water under interfluves of the land. Rain water descends at once to join a deep-lying body of ground water with a more or less horizontal surface, or water table, the level of which is controlled by that of the lowest available outlet; and through this the water gushes out as a ready-made river, or joins one of the few main streams draining the region in the bottom of its deeply cut valley (Fig. 345). The gradual descent of the water table as passages are opened by water seeping down through a hitherto dense and rather impermeable limestone has been thus described:

The slowly moving water . . . gradually enlarges the small openings in the rock by solution, and its movement is slowly concentrated along certain lines until tiny channels are developed. Such channels afford freer movement for the underground waters. . . . With the concentration of movement along these lines the channels are rapidly enlarged, and as soon as their capacity becomes sufficient the ground-water table is brought down to their level. (WELLER.)[26]



V. D. Zotov, photo

Fig. 346. Subaerial solution potholes on a limestone surface, Mount Cass, Canterbury, New Zealand. Size, up to 8 inches in diameter.

When the water table has sunk far below the ground, small surface streams, such as occur in branching systems on other terrains and dissect the land surface, are non-existent or very rare, though some may be present that are related to "perched" ground water held up by local intercalations of impermeable rock. In places where, owing to the nature of the relief, the ground water is never at a great depth seasonal fluctuations of the ground-water level may cause a few streams to flow intermittently, as in the case of some on the chalk terrain of England.[26] In the absence of surface streams there can be little or no valley development by mechanical corrasion or normal dissection of the surface. There is very wide spacing of valleys and the texture of normal dissection is very coarse, but the place of dissection by minor streams is taken by a pitting that results

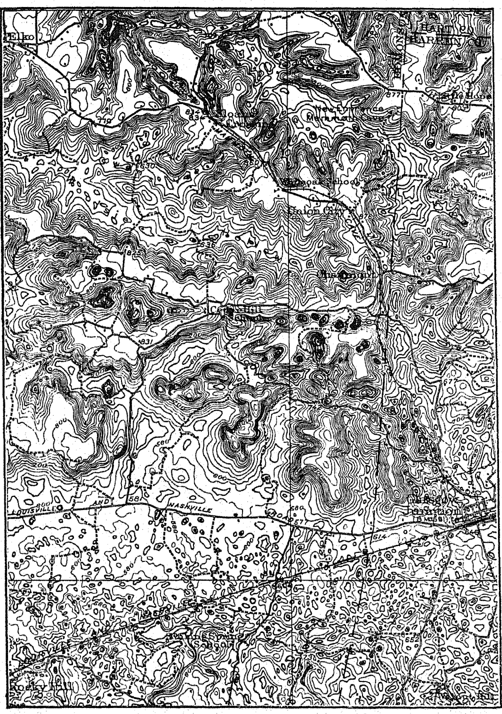


Fig. 347. Limestone relief, with very numerous large sinkholes, in the Mammoth Cave district of Kentucky. Scale: about ¾ in. = 1 mile.

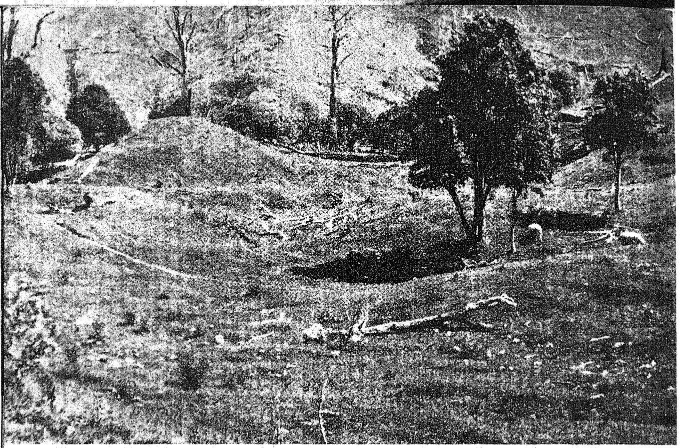


Fig. 348. Minor relief features on limestone. Surface pitting has developed as the drainage has gone underground in channels opened by solution, Ruakokopatuna Valley, Wairarapa district, New Zealand.

from development of features related to underground solution, and in this way a "fine-textured" surface of a special kind may result (Figs. 347, 348).

Funnel-shaped, or occasionally precipitous-sided, sinks (*sink-holes, swallow holes,* in France *avens,* or in the Dinaric karst region *dolines*) varying in diameter from a yard or two to about a thousand

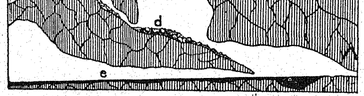
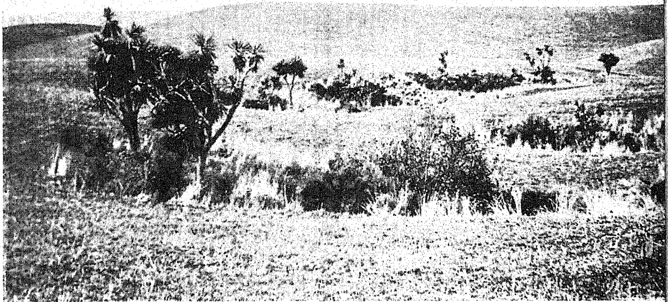


Fig. 349. Relation of sinkholes (*a, b, c*) to caverns and underground drainage (*d, e*) in limestone (After Cvijić).
(From *Geomorphology,* also by the author.)



M. C. Gudex, photo

Fig. 350. Sinkholes in the Pareora district, South Canterbury, New Zealand.

yards (Figs. 349-352, 356), are related to enlarged fissures below ground, which lead water down into caverns and open galleries that are underground stream courses (Fig. 349). They do not, as a rule, remain as open pits of great depth, but are partly choked by debris fallen from the sides and washed in from the surface; and they may thus hold perched water for a time after heavy rains. Lakes are present in some deep dolines (Fig. 352). If the floor of the

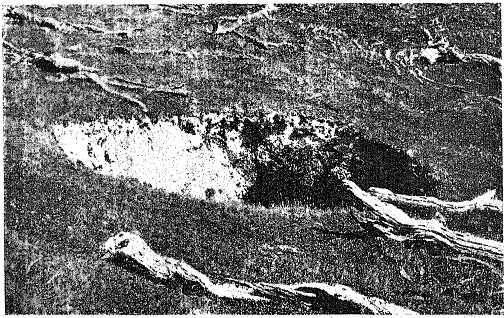


Fig. 351. A small sinkhole ("aven" type), Wairarapa, New Zealand. (From *Geomorphology*, also by the author.)

doline is below the water table at all times of the year the lake is permanent, but in other cases the doline dries out seasonally owing to the fluctuation of the level of the ground water. Such lakes in dolines are natural wells like the "cenotes" of Yucatan (p. 472).

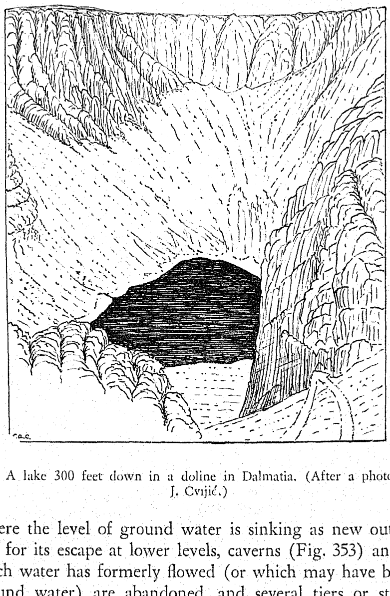


Fig. 352. A lake 300 feet down in a doline in Dalmatia. (After a photograph by J. Cvijić.)

Where the level of ground water is sinking as new outlets are opened for its escape at lower levels, caverns (Fig. 353) and shafts in which water has formerly flowed (or which may have been full of ground water) are abandoned, and several tiers or stories of caverns may be thus left—as at Jenolan Caves, New South Wales—the empty caverns being afterwards partly filled with "dripstone" deposits (Fig. 374) consisting of calcite redeposited as stalactites and stalagmites. Anciently enlarged caverns and underground stream courses may be found in a more or less ruined and unroofed condition, and, if still traversed by streams of water, may become

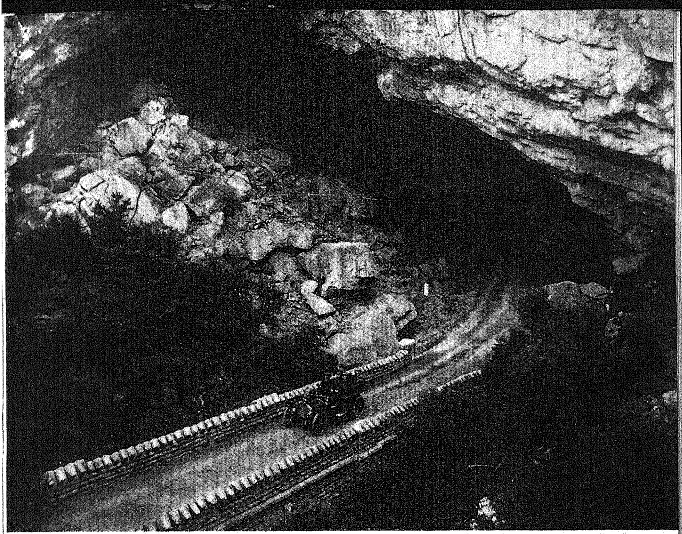


Fig. 353. The entrance to the Jenolan Caves, New South Wales.

river gorges, with perhaps occasional remnants of the roofs forming "natural bridges".[6, 22] Arches that have originated in this way appear in Fig. 354. An alternative explanation that has been offered for some natural bridges in soluble rocks is that rivers have abandoned courses over falls of the Niagara type, making their way along fissures enlarged by solution so as to issue below the edges of their former falls by way of underground courses which are subsequently enlarged. Celebrated natural bridges in limestone formations are the great Natural Bridge of Virginia[15] (Fig. 355) and that in the gorge of the Rummel, at Constantine, in Algeria, figured by de Martonne.[18]

Several sinkholes may be arranged in line in such a way as to indicate the presence of an underground river. (One of such a series is figured in Fig. 356.) They may be aligned along the bottom of the valley of a former surface stream that has ceased to flow owing to lowering of the ground-water level, or, on the other hand, may be the first stage in the unroofing of an underground water-course in process of transformation into a gorge (Fig. 357).

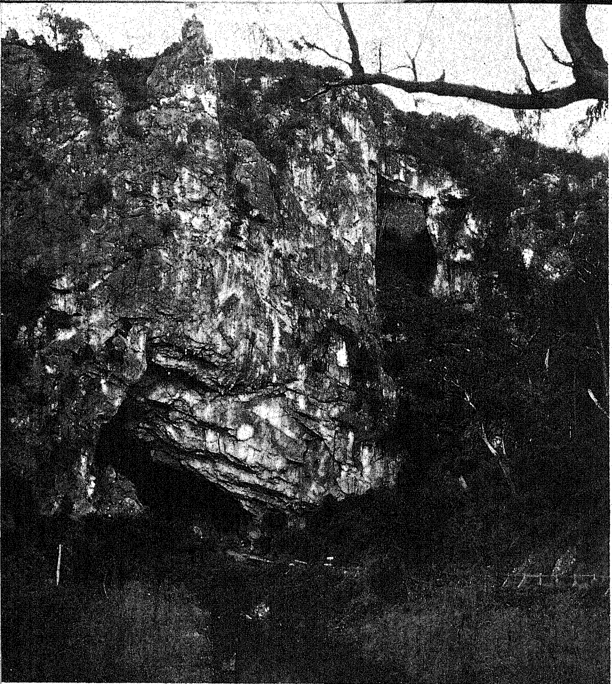


Fig. 354. Natural arches in limestone at Jenolan, New South Wales.

Where, in the Dinaric karst region, a surface stream plunges into
an open vertical shaft that has been enlarged by solution, this is
termed a *ponor*, or the place of these more or less circular shafts
may be taken by narrow, elongated chasms (*bogaz*). If a stream
Valleys occupied by surface streams that issue from caverns may
flowing in a valley disappears underground in what the French
call a *perte*, the abruptly terminated valley is described as "blind".
have a similar form at the head.

The last residuals of a limestone stratum that is wasting away by solution where it rests upon non-calcareous rocks are *hums* (Fig. 358), but the term is applied also to any small "monadnocks" of limestone in the Dinaric karst region.[6, 22] Small residual mesas, or "hums", of limestone, riddled with caverns, remnants of a sheet formerly continuous over the now resurrected fossil plain of the plateaux of northern Nelson, New Zealand, have been referred to in Chapter XVII (Fig. 364).

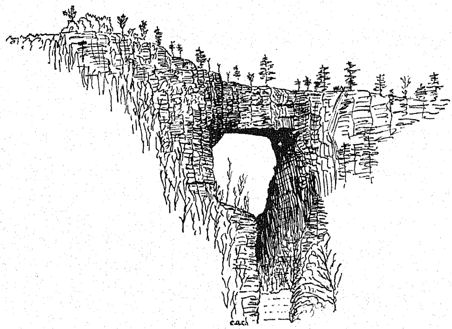


Fig. 355. The Natural Bridge, near Lexington, in Virginia.

The various features mentioned and described without system in the foregoing pages as characteristic of the erosion of limestone may be present sporadically throughout parts of a limestone terrain that is undergoing normal erosion and exhibits elsewhere typical mechanically eroded valley forms. They interfere in such cases only locally with the development and progress of a landscape through the normal stage of maturity. In other cases, however, these special forms are developed in such profusion as to diversify the surface to the exclusion of features of normal stream origin. Other conditions being favourable, such replacement can take place rapidly only if channels have already been opened in the limestone, or if there

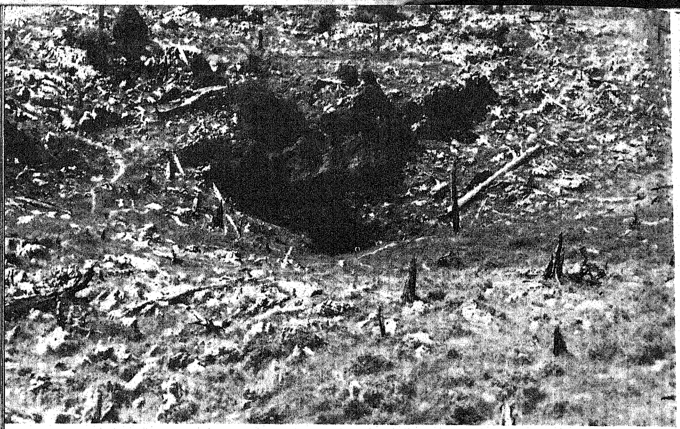


Fig. 356. A sinkhole and karrenfeld on the Pikikiruna Range, Nelson, New Zealand.

are abundant joint fissures in it affording initial channels which can be enlarged by solution when entered by water descending from the surface.

To a certain extent the development of features related to underground solution is independent of climate, but a seasonal variation of rainfall may result in a considerable seasonal change in the level of the water table (level of saturation) in the underground rocks. Where this occurs to an appreciable extent it leads to alternation of normal erosion by surface streams with erosion by underground solution in parts of the districts affected, and this may be a reason for the particularly full development of the "limestone" or "karst" cycle, or cycle of erosion by solution, in the extensive Dinaric limestone region.

The Normal Geomorphic Cycle Modified by Karst Conditions

Where the relation of a mass of limestone rocks to general base-level and to associated relatively impermeable formations determines that the water table shall not descend to such a depth as to rob surface channels of their streams, erosion on limestone follows the

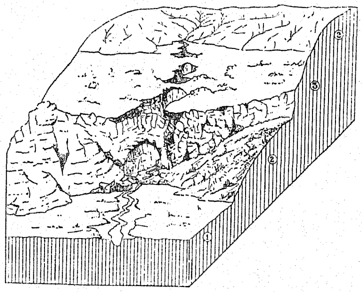
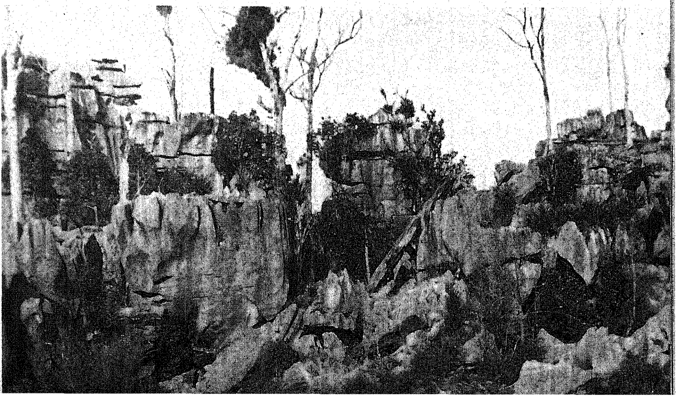


Fig. 357. Transformation of a cavern into a gorge in a tributary of the Danube in eastern Serbia; 3, limestone intercalated between sandstone layers, 2. (After Cvijić.)

(From *Geomorphology,* also by the author.)

Fig. 358. A large wasting hum of limestone in the Whangarei district, New Zealand.



same course as on other terrains—that is to say, normal systems of valleys are eroded and the normal cycle of erosion (with some variations at the stage of maturity) runs its course towards eventual peneplanation. If the water table sinks after some development of valleys has taken place, the normal submaturely or maturely dissected landscape will be abandoned to some extent by the streams that have eroded it, all but the largest of these (in the most deeply cut valleys) taking to underground courses.

All valleys at higher levels become "dry" valleys, and only a few of the larger and deeper valleys, into which the underground streams discharge as springs, remain occupied by rivers and continue their normal development. If the cycle of erosion be not far advanced, these may continue to deepen their valleys as steep-walled trenches, causing the water table to descend still deeper, while the valley systems of their former tributaries will be left stranded on a dry upland landscape, perhaps approximating to a limestone desert like the plateau of the Causses, in southern France, most of which is without a normal pattern of dissecting valleys, though it is traversed by a few deep trenches, such as the "canyon" of the Tarn River, 2000 feet deep.[18]

A locally conditioned lowering of the level of the ground-water surface is believed to have caused the abandonment of valleys that are now dry on the chalk terrain of south-eastern England. Recent retreat of an escarpment of the permeable chalk formation, accompanied by development of valleys to progressively deeper levels in underlying impermeable strata as they have been uncovered, has lowered the water table.[27]

Abandonment of the surface channels by superficial streams has not been followed in this case by "karsting", or replacement of normal landscape forms by the pitted surface characteristic of more compact limestones when they are swallowing surface water through sinkholes, for in chalk the lithological nature of the material does not favour extensive development of underground passages, perhaps because the chalk substance as a whole is highly permeable. Thus the maturely dissected surface retains the graded slopes characteristic of maturity in the normal cycle; but it assumes a coarse texture of stream spacing. The dominance of broadly convex slopes is related to the chalk lithology, as has already been shown in Chapter XIV. It produces the "downs" type of landscape.[18]

Dry valleys in a chalk terrain, as on other limestones, may be cut off and left as hanging valleys owing to a continued erosional deepening of main valleys that still contain surface streams.

The Karst Landscape

In the Dalmatian holokarst terrain the history of karst development, as interpreted by Grund,[12] Penck,[21] Cvijić,[4-6, 22] and other workers in that region has begun with uplift of a peneplain that had been developed on the terrain of pure limestone, or rather of a

Fig. 359. Aligned dolines in a dry valley on a limestone plateau in Serbia. (After Cvijić.)

peneplain already dissected to low relief by the development of shallow, widely open, normal valleys. Development of underground drainage has led, however, to abandonment of these valleys by streams so that their floors have become pitted by dolines. This early stage of karst development is illustrated in Fig. 359.

Blind Valleys and Tectonic Poljes

The peneplain of the holokarst region was not uniformly upheaved to form the initial plateau of the limestone desert, or karst, but this is interrupted by large relatively depressed areas of tectonic origin. Thus many mountain-rimmed basins in the region are interpreted as originally grabens. These and some others that are classed with them as *poljes** are without outlets on the surface,

* The spelling adopted by Douglas Johnson in his accounts of this limestone region as a theatre of war in 1914-1918 is "polyes", and this indicates the pronunciation of the word.

but are drained instead through caverns by underground rivers or by leakage and infiltration into the slowly moving ground water. As the Jugoslav term "polje" is applied in common language to basins of various sorts and of various origins, it is as well to distinguish those that have been initiated by earth movements as "tectonic" poljes (Figs. 360, 362). Warping as well as faulting may be concerned in the origin of these.[10] In some cases tectonic origin

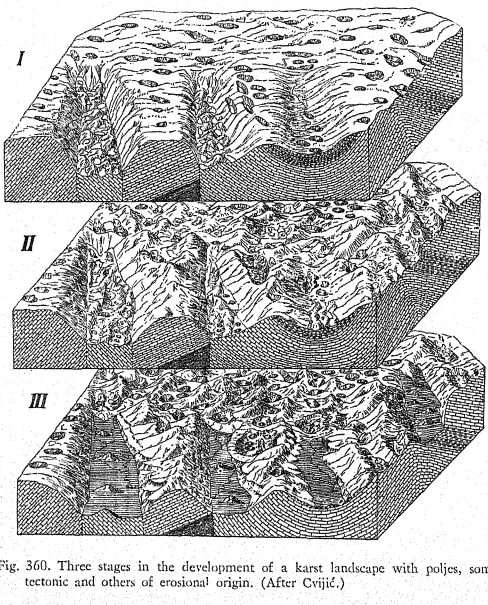


Fig. 360. Three stages in the development of a karst landscape with poljes, some tectonic and others of erosional origin. (After Cvijić.)

is attested by geological evidence such as the dislocation (as reported by Cvijić[6]) of alluvial deposits, those at low levels on some polje floors having been formerly continuous with others that are now perched on flanking highlands.

In addition to tectonic poljes there are some in the Dinaric region that are explained as related to the ancient structure, which has controlled differential erosion on the terrain—i.e. they have been excavated in downfolded and downfaulted masses of weak rocks. De Martonne[18] has cited some poljes of very large size, up to 50

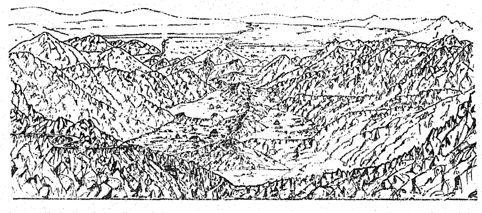


Fig. 361. Uvalas coalescing to form a polje in Montenegro. Beyond the polje is the Lake of Scutari. (After Cvijić.)

kilometres long, as examples of those related to structure of the terrain as revealed by differential erosion. The syncline shown in Fig. 360 is, unlike the faults that are also figured, part of the ancient structure, and a subsequent valley aligned on it has been further developed by the karst processes (as indicated) into a polje. In the floor of such a valley, e.g. that shown in Fig. 359, subsurface drainage opens a line of dolines; rivers that have flowed in the valleys have thus become first segmented and then eliminated, groups of dolines have become integrated to make the larger hollows termed "uvalas", and these coalesce eventually to make a polje. (Figs. 360, 361). All this can be brought about by sinking of the water table, and such sinking, in a region in which underground channels are either present or can readily be opened, will take

place when main valleys are deepened* because the rivers flowing in them are rejuvenated by a regional upheaval.[25] An example (figured by Cvijić[6, 22]) of a polje developed from a river valley without profound karstic modification of the relief is that of Kostan, near Novi Bazar.

It is true of the whole upland surface that as soon as the ground water has sunk far enough below ground to eliminate surface streams "karsting" becomes general—i.e. the surface will be pitted by innumerable large and small swallow holes of various kinds and will continue to sag down and collapse so as to develop more or less steep-walled uvalas with diameters of up to a kilometre and even more (Fig. 360). Poljes of erosional origin are referred to by Davis as blind valleys, however large they may be. They are known in many regions, being reported, for example, in Jamaica (where they are known as "cockpits") and in Java, by Daneš,[9, 18] while the "katavothres" (ponors) of the Peloponnesus (Greece) are in closed basins of the same kind.[17, 18]

In an early stage of landscape youth, when drainage of the whole region might be for a time superficial, tectonic poljes might contain water which would spill out of them by way of surface streams; but this condition would soon give place to one in which the enlargement of fissures by solution lowered the water table to such an extent that much drainage was led off through underground channels. Thus some (though not all) tectonic poljes are now without outlet gorges. As shown in Fig. 362, a diagram designed by Grund[12] and reproduced by Penck,[21] the courses of underground rivers draining from some such poljes may be considered in a sense antecedent, if they follow more or less the same lines as former surface streams in existence before the poljes were initiated by upheaval of their rims.

* It must be pointed out that statements made in the text implying control of the level of the water table by either the general base-level or a local one furnished by rivers in the deeper valleys are not based on Cvijić's[6] interpretation of karst features. That author does not state that either the upper (wet-season) or the lower (dry-season) water table is controlled by the level at which escape of water to the surface can take place. Throughout the development of the karst landscape (karst cycle) he pictures the water table as lowered progressively towards the base of the limestone formation (regarding this as the only control, however deep it may be) as joints and fissures are progressively enlarged by the solvent action of descending water.

Because of the great seasonal fluctuation of the level of the water table (Fig. 362) ground water wells out as voluminous springs, and considerable parts of the floors of some poljes are thus flooded in the wet season. Even where flooding does not take place, surface streams can then flow, and there is a local base-level of stream

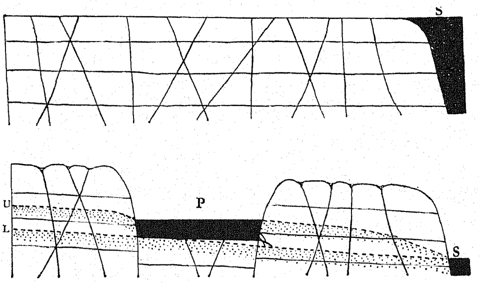


Fig. 362. Origin of a tectonic polje that has been produced by differential upheaval of a well-worn surface, as in section above, on a limestone terrain. P: Polje; S: sea-level; U. L: upper and lower limits of fluctuation of the level of the water table, which leads to seasonal inundation of the floor of the polje. (After Grund and Penck.)

erosion. Thus extensive and nearly level floors, which are present in many of the large poljes, are regarded as having been reduced to small relief by a process of local peneplanation. There are in places flat floors "of truncated limestone" (Davis), but in places the floors are now aggraded or covered in part with lake silts, while the unconsumed monadnock-like hills of limestone referred to as hums remain here and there. As an example of a large polje of tectonic origin much modified by erosion, so that it has now a great area of level floor diversified by residual hills, Cvijić figures that of Niksić, in Montenegro (Fig. 363). Davis has described similar features as follows:

Among the many poljes that have no outlet gorge, one of the simplest examples that we saw occupied a depression in the uplands west of Mostar; it is known as the Mostarsko Blato. Its floor . . . is of oval outline, with axes measuring about seven and two miles. . . . The surface of the polje is smoothly aggraded with fine silt. The uplands are pasture grounds; the polje is laid out in fields, largely submerged in winter, still partly submerged . . . late in May, but dry enough for cultivation or pasturage in the late summer, although a small lake remains even then in the south-eastern part of the plain. The drainage is effected at time of high water by discharge into an ugly cavernous hole, known as a ponor, at the rim of the polje plain, and at all times by underground percolation.

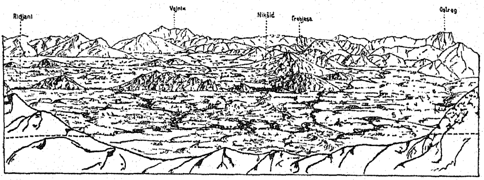


Fig. 363. The polje of Niksić, in Montenegro. (After Cvijić.)

The waters reappear after a subterranean passage of two miles in a great spring, which fed a good-sized branch of the Narenta. . . . A much larger enclosed basin was that of the Nevesinje, fifteen miles long and three or four wide . . . from which several streams find underground escape through different ponors. Here the floor of the basin was gently rolling. Much of the underground water from this gathering-ground reappears ten miles away . . . in the great Buna spring . . . from which a vigorous stream runs to the Narenta. (Davis.)[10]

In glacial epochs, according to Cvijić,[4] the water table has been higher, and this accounts for the existence of permanent lakes at such times in the poljes, which have left deposits on their floors.

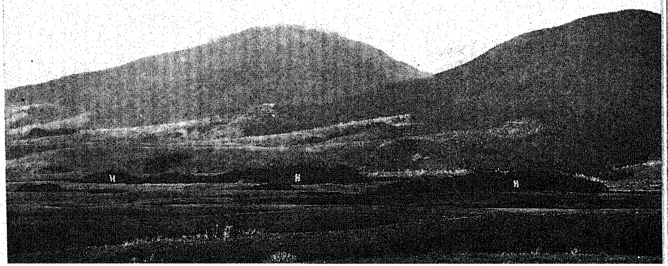
Certain poljes seem to have been developed in two stages, an inner floor being excavated to a level considerably lower than that indicated by benches which are berms of an earlier floor, and this probably means that the local base-level, governed by the water

table, has sunk from an old to a new fixed level. In two examples about twenty miles north of Trebinje, Davis[10] has described the poljes as "the lower compartments of a double-floored basin, the lower floors lying about 200 metres beneath the rimming remnants of what must have been once a much larger upper floor. Both floors were about horizontal, and both truncated the strongly inclined limestone strata."

Erosion Cycle on Limestone with Base above Sea-level

A positive check to the lowering of local base-levels that results from progressive sinking of the water table is given by exposure of relatively impermeable formations beneath the limestone. Where the conditions of structure make this possible, the eventual removal by erosion of the limestone cover from an area thus floored with non-calcareous rocks is regarded as marking the "old-age" stage in a variety of the karst cycle specially related to this type of structure. When such "old age" is reached, only isolated hums of cavern-riddled limestone remain scattered over a landscape developed (or developing) on the underlying rocks. This is the stage that has been reached in the removal of a sheet of limestone from the plateaux of the Nelson province of New Zealand, with exposure of an underlying fossil plain (Figs. 233, 364). The limestone residuals on these

Fig. 364. Bush-covered limestone hums (H) are the last residuals of a sheet of limestone that formerly covered a fossil plain since resurrected to form the Gouland Downs plateau, Nelson province, New Zealand.



plateaux, which are referred to in Chapter XVIII, are hums (Fig. 364). Cvijić's[6] diagram (Fig. 365: 4) of the "old-age" stage of the karst cycle as thus developed shows that it is not necessarily a stable or long-enduring type of landscape; it is, therefore, not truly senile or at all comparable with a peneplain. It is instead merely the

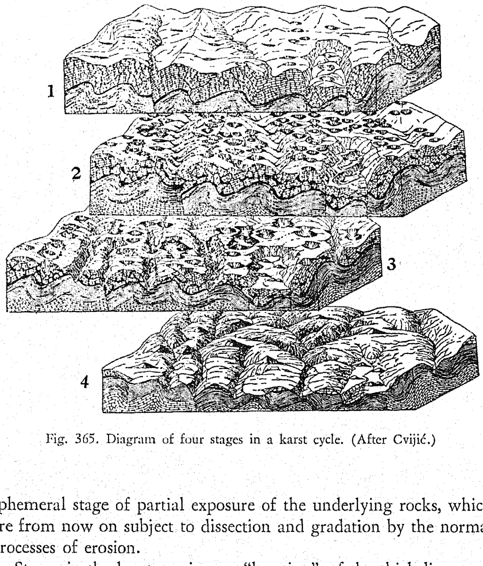


Fig. 365. Diagram of four stages in a karst cycle. (After Cvijić.)

ephemeral stage of partial exposure of the underlying rocks, which are from now on subject to dissection and gradation by the normal processes of erosion.

Stages in the karst erosion, or "karsting", of the thick limestone cover pictured by Cvijić as leading up to the "old-age" stage, or (4) in Fig. 365, are (1) "youth", (2) "maturity", and (3) "late maturity". In (1) some karst features, which result from sinking of the water table, are making their appearance as modifications of an initial surface that has been prepared for karsting by removal,

perhaps in an earlier cycle of normal erosion, of overlying non-calcareous strata so as to expose an undulating structural plateau, or a peneplain, of limestone varied by superposition on it of some streams from normal valley systems of the now vanished cover. At stage (2) all surface water is swallowed by abundant dolines and uvalas, which have developed to the extent of becoming the dominant features of the relief. At stage (3) new open valleys appear along the lines of the main underground stream courses of the previous stage, exposed now by foundering of their roofs, and carrying permanent streams of water perhaps, but not necessarily, because they have been cut down through the limestone into the underlying rocks.

The conditions of structure making possible the development of a landscape through the "mature" stages of the karst (typical karst forms) to the ideal "old age" of this cycle—i.e. presence of a floor of impervious rocks below the limestone and above sea-level—are found only in certain parts of the Dinaric limestone province, as is shown in Cvijić's[6] large and beautifully designed generalised diagram of the karst structures and relief typical of that region.* Local reduction of the floors of poljes to small relief in relation to local base-levels is seen also to be merely an episode in the general reduction of the relief of the region in relation to a general base-level, which is sea-level.

The Limestone Cycle According to Davis

Various authors,[12, 23] including Davis,[11] have pictured the geomorphic cycle on limestone as not radically different from that on the less soluble rocks. As viewed by Davis, karst features, which he terms "those of the so-called karst stage of development," appear in only one stage, early maturity, of the geomorphic cycle. Then, on limestone terrain, "large funnel-shaped sinks occupy the greater part of the surface, leaving little more than sharp edges between them. Many streams that ran on the surface in the youth of the region are now segmented at swallow holes and led underground".

Davis has briefly discussed the forms of a "first" cycle on limestone, but his analysis may be applied to *n*th cycles also:

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* Reproduced in the *Geographical Review*, 11, Fig. 11, p. 603, 1921.

At a later stage than that of karst development . . . groups of sinkholes seem . . . to blend together . . . forming "blind valleys", i.e. somewhat elongated and fairly broad depressions occupied with close-set shallow sinks; or, if smoothly floored, drained by streams which disappear in cavernous passages. Surviving residual hills between these depressions may still contain caverns . . . the remains of previously longer gallery systems. [The landscape of the Mammoth Cave district, in Kentucky, is cited as an example (Fig. 347).] . . . Disappearing rivers . . . associated with blind valleys are the surviving segments of water courses that initially had a continuous surface flow, but which, with the increasing development of sinkholes, are now increasingly lowered to underground courses. They not infrequently disappear and reappear. (DAVIS.)[11]

When, according to Davis, the senile (peneplanation) stage is entered on,

the floors of normal and blind valleys are slowly broadened and the residual ridges between them are worn down. . . . Cavernous passages will have been unroofed and opened to the air; but they will no longer look like caverns, for the walls will have been worn down to grade. (DAVIS.)[11]

De Martonne[18] describes a choking of underground channels at this stage:

The general lowering of the surface progressively reduces the depth of the dry zone [above the water table]. At the same time the saturated zone extends upward, for the argillaceous residue from decomposition of limestone, the *terra rossa,* is increasingly abundant, and, as . . . subterranean streams are no longer capable of carrying this away, their channels are choked . . . and underground drainage becomes less active. So a time will arrive when water will make its appearance in the poljes and in the bottom of dolines, and their inundation, temporary at first, will become more or less permanent. . . . Water courses will appear at first on the polje floors generally as intermittent streams, but eventually systems of rivers in ordinary open valleys are reconstructed, and normal sculpture begins again. It is death of the karst. (DE MARTONNE.)[18]

Choking of passages cannot be the sole or even the chief cause of the reappearance of rivers, however. The valleys have been deepened to such an extent that the ground water is now close to the surface and the water table intersects the surface. Movement of

ground water below the local base-level must be sluggish, and much of the run-off must, therefore, take place above ground. There is some inconsistency also in postulating that underground river courses have previously been in existence below the water table when the French theory of "torrential" erosion by vadose water is relied on in explanation of all large open passages (Chapter XXIV).

In a second or later cycle of erosion Davis has pictured conditions that must lead to a rather rapid development of the surface forms characteristic of the karst stage of landscape development. The cycle is assumed to be introduced by uniform uplift. Then,

accompanying and following the movement of elevation, the . . . cavernous galleries of ground-water solution in the preceding cycle will be drained of the water filling that occupied them during their slow excavation; and the peneplain [initial form of the new cycle] will enter a second cycle of erosion with a full equipment of already-made underground shafts and galleries, thus eliding the gradual development of shafts and galleries by which a first cycle is characterised. (DAVIS.)[11]

This analysis obviously depends on acceptance of the theory of excavation of caverns considerably below the water table—the deep-solution hypothesis favoured by Davis (Chapter XXIV). Thus he continues:

If a rapidly and recently uplifted limestone peneplain be somewhere found, trenched by narrow and steep-sided valleys, the caverns to which the young valleys give entrance may be found so extensively developed as at once to suggest their origin before uplift occurred. . . . In consequence of uplift the water filling of the solutional caverns will be withdrawn, with the result of for a short time provoking active rock falls from the roof . . . A further consequence . . . will be the active corrasion of shafts and galleries along which the withdrawal of the water filling takes place. (DAVIS.)[11]

EXAMPLES OF LIMESTONE LANDSCAPES

In the extensive and thick limestones of the tropical belt landscapes developed largely by solution are common. The limestones of some of these terrains are nearly-level bedded coral and shelly strata which remain more or less porous, but in other cases—in Cuba and at many places in south-east Asia, for example—there are old and

compact limestones which in parts are steeply inclined and folded. On all these terrains typical limestone-cycle, or karst, forms are developed; but the rate at which the solution cycle proceeds has been found to vary greatly with the porosity. There is, nevertheless, a strong family resemblance among the resulting relief forms.

Youth, as exemplified on upraised coral reefs, is characterised by the development of extensive karrenfelds of the makatea type. In Florida, in a limestone region that is lowlying and of small relief, there are many sinkholes and blind valleys. The low limestone coastal plain of Yucatan[3] is not dissected by valleys. "Such a thing as a river is unknown. Not even a brook is found in the whole region, and naturally there are no valleys either" (Huntington). Sinkholes with precipitous sides extend down below the water table and function as wells. These natural wells, known as "cenotes", are about 100 feet deep and 100 to 200 feet in diameter. A current theory in explanation of their origin is that the openings developed upward, as dome-shaped chambers were formed by caving of the roof in the vicinity of vertical cracks above a cavern zone already containing ground water capable of dissolving fallen blocks. It is possible, however, that the invasion of accessible parts of the cenotes by water took place only after the water table rose to its present position along with a rising ocean level. The limestone is for the most part weak and porous, though a superficial layer is somewhat indurated.

A plain similar to that of Yucatan, but in a region of very scanty rainfall, is the coastal plain that fringes the Great Australian Bight in South Australia. It consists of cavernous limestone, sub-crystalline superficially but porous in texture below, for a width of about 100 miles. This limestone plain, part of which is known as the Nullarbor Plain, is only very slightly undulating (a form probably structural or tectonic) and rises very gently inland from sea cliffs 200 feet and more in height. It is without surface streams or valleys, but there are numerous small and a few large and deep sinkholes, the latter due apparently to collapse and subsidence of the surface over caverns, and the extent of these is further indicated by in-blowing and out-blowing air currents at "blowholes" according to the condition of atmospheric pressure. Some caverns, which are accessible by way of the deepest sinkholes, are known to intersect the water table, and the deeper parts of them contain standing saline ground water.[25]

On many limestone terrains with greater available relief erosion has proceeded to and beyond the karst stage, and a condition that is commonly found is one of post-maturity ("death of the karst"), in which many streams have returned to the surface, as pictured in de Martonne's generalisation, though the valleys in which these flow may still be separated by interfluves of considerable relief.

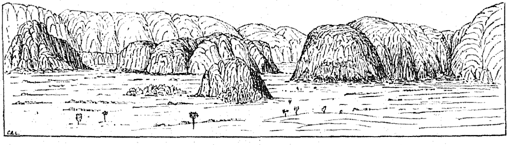

Fig. 366. Cuban limestone landscape, Sierra de los Organos. (Drawn from a photograph.)

Through these in places streams still flow in caverns, but the interfluves have very commonly become disintegrated and reduced to isolated residuals. Of this nature are "mogotes", described as "huge castle-like residual masses of limestone between flat-floored valleys";[11] they are "riddled with cavernous passages".[11] The typical mogotes are residuals of the old folded limestones of the Sierra de los Organos, in western Cuba[2, 19] (Fig. 366).

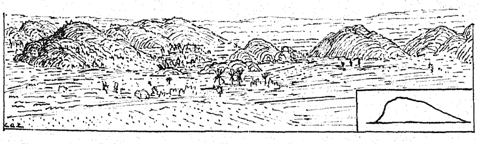

Fig. 367. Cavern-riddled haystack hills near Bayamon, Puerto Rico, showing the gentler, windward slopes. Inset: characteristic profile. (Drawn from photographs.)

Similarly shaped hills are found in Jamaica,[9] and of similar origin are the "pepino"[1] or "haystack"[14] hills of Puerto Rico. The smaller size of these and their closer spacing as compared with the mogotes of Cuba are explained by Meyerhoff[18] as a consequence of smaller available relief (Fig. 367). They are residuals of the gently tilted

coral and shelly limestones that form the northern coastal plain of the island. These hills display a pronounced asymmetry of form which is attributable to greater exposure to the erosive activity of rain on the side (east-north-east) that faces the prevailing strong wind.[24] On the windward slopes, on which most of the rain falls, the surface is reduced by solution to a gentle slope, whereas on the lee side it remains steep, with some vertical and even overhanging cliffs.

Fig. 368. The "needle karst" forms (high-peaked hums) of Kwangsi, China. (Drawn from a photograph.)

In south-eastern Asia (China, Indo-China, Malaya, and Burma) an advanced stage of erosion has produced on old limestones in some localities a type of landscape that has been called "needle karst". Numerous high residuals have been isolated after the fashion of mogotes or pepino hills, and may remain closely spaced; but instead of haystack forms sharper pyramids are characteristic of the relief. In Burma these are described as producing an effect as of "unexpected alpine landscapes in lowlying flood land and marsh land" (Sawicki).[23] Among the best known of these fields of high-peaked hums is one in Kwangsi which is said to have been adopted as an exemplar for mountain forms in Chinese pictorial art (Fig. 368). There are somewhat similar pyramids of limestone, very

closely spaced, however, and obviously isolated by solution that has worked along vertical joints, in the Durance valley, in France, in a brobdingnagian karrenfeld.*

Rimstone Constructional Forms

In limestone regions deposition above-ground of calcium carbonate from lime-saturated water is occasionally responsible for the development of features of some importance. Where such water emerges from underground channels as springs, or is broken by cascades where flowing in open courses, "rimstone"[11] deposits of calcareous tufa in the compact form of travertine may be formed. Thus falls may grow forward instead of retreating by headward erosion as they do in other rocks. The beautiful cascades at Tivoli, near Rome, are advancing in this way, and so also are many in the Dalmatian limestone region.[11a] Rimstone bars of tufa or travertine built in river valleys where they are entered by springs emerging from caverns have ponded rivers in Dalmatia, forming lakes. A notable example is the Kerka River, dammed by travertine to form a large lake, the overflow falls from which supply a coastal town with power. An Australian example of a large river that leaps over "constructive" waterfalls formed by travertine bars is the Gregory (as Daneš[9] has described), which is fed by ground water from beneath a limestone plateau south-west of the Gulf of Carpentaria. Harrison[13] mentions a tufa bridge across the Yauli River, in Peru.

The overflow from mineral springs (siliceous as well as calcareous) builds up rimstone deposits of geyserite or of travertine which eventually may enclose lakelets. This takes place extensively around hot springs in the Rotorua district of New Zealand, where the rimstone is siliceous. Emerging at the summits of calcareous rimstone mounds there are in Central Australia many voluminous "mound" springs, which afford the only natural outlets for water trapped in the vast Australian artesian basin.[25] The mounds that have been built in this way vary in size, but some "rise to heights of 130 feet above the present general surface level, and some . . . ancient mounds covered individually an area of several square miles. . . . In a few cases . . . there is an almost circular water-filled crater on the crest." (Ward.)[25]

* Figured by A. K. Lobeck, *Geomorphology*, 1939 (see p. 114).

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CHAPTER XXIV

Limestone Caverns

THE QUESTION OF THE ORIGIN OF CAVERNS IN LIMESTONE IS SO CLOSELY related to that of the development of the landscape on the surface that it becomes a matter for geomorphic investigation. On an earlier page enlargement of underground passages has been confidently ascribed to solution, and there is general agreement that the chemical process of solution (sometimes referred to as corrosion) at least begins the enlargement. Yet many authors specifically attribute most of the opening, or excavation, of shafts and galleries to mechanical erosion by descending water.

GROUND WATER IN LIMESTONE

Much of the theory of the development of holokarst landscape and even of limestone erosion in general depends on the question of the existence of a water table in limestone and of the relation to the water table of a major zone of subterranean erosion and horizontal excavation. After open underground passages have been developed the ground water naturally sinks until the water table is very flat and nowhere far above the level of the lowest available outlet to the surface.[22, 25] Many limestones, which are relatively impermeable rocks to begin with, however, remain so until passages have been opened through them by solution, and this process may be long delayed in those parts of the rock mass in which joints are scarce, though if joints are present they are soon enlarged by solution as water from the surface passes down through them. If there are barriers formed by bodies of unjointed rock that remain impermeable between systems of underground drainage channels, ground water will be enclosed in compartments and the level of its surface thus held up in some places. So also there may be perched water in compartments walled by bodies of impermeable non-limestone rocks present as dykes, anticlinal cores, etc., or held up above intercalated beds or sills. Descending streams of water pirated from the surface,

as well as siphon-shaped channels that remain full of water, may be found at various depths. Such facts, together with the great depths below ground at which exploration of air-filled passages has been carried out, have led to some disbelief in the presence of ground water and therefore of a water table in limestone terrains.[2, 13] If the limestone extends deeply enough, however, it cannot be questioned that such open spaces as are present in the deeper part of it will be full of water. Under appropriate conditions of structure some limestone strata are found to yield artesian water abundantly.[23]

Martel[13] reports a prolonged controversy (eventually declared closed in 1911) between geomorphologists of the Vienna school (Grund[6, 7] and others) and cave explorers on the question of whether there is ground water (*Karstwasser*) moving so far as it can as a sheet through such channels as have been opened sufficiently in the deeper part of the limestone, or whether, as Martel and the cave-investigators have maintained, underground rivers, which undoubtedly exist, are in no case part of a continuous body of water. There seems to have been a distinction made without much difference except in terminology. Penck,[18] who has supported the ground-water theory—i.e. Grund's theory of "karst water", which amounts to the same thing—allots an important part also to the "karst rivers" underground, which flow with free surface through caverns and are in a sense distinct from the ground water. Such underground rivers must be closely related to the ground water, however, just as rivers above ground are.

The observations of Cvijić[3] in the terrain of pure limestone east of the Adriatic Sea indicate that the descent of water, at least above the surface of the ground water, which is generally at a great depth there, takes place nearly vertically through passages which have been enlarged by the descending water. He has found no resemblance between underground water courses in limestone and the superficial water streams on other rocks, which work to a base-level.

The Question of Underground Corrasion

French geologists and geographers, especially de Lapparent,[10] Haug,[8] and de Martonne,[14] have championed the theory, which has been maintained also by cave explorers (led by Martel)[13], that galleries and all other large open spaces underground are or have been parts of the courses opened and enlarged for themselves by

vigorously flowing streams of water that have descended as such from the surface, taking with them some of the rock debris they make use of in the process of corrasion, or, as it is termed by French authors, "torrential erosion".[15] The experienced investigator Martel[13] not only considers "mechanical erosion more powerful than corrosion" underground but makes it clear that he pins his faith to corrasion as the greatly preponderant process active in excavating

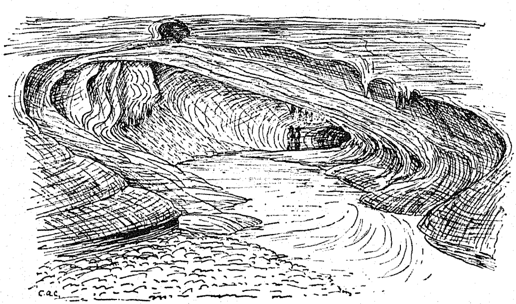

Fig. 369. Forms attributed to whirlpool erosion in a cavern traversed by the underground river La Bouiche, Ariège, France. (After a photograph by Martel.)

caverns. Martel has stressed the importance of potholing, or whirlpool, erosion underground and has figured some of its effects (Fig. 369). On the other hand it seems probable that some underground streams that are voluminous and sluggish do much of their erosive work by corrosion (Fig. 373).

Some other investigators, notably Daneš,[4] Lobeck,[11] Weller,[26] and Malott,[12] have adopted the French theory of extensive underground corrasion; but cogent reasons for rejecting it have been stated by Davis,[5] who is followed by Piper[19] and Swinnerton.[22, 23] It is the well considered opinion of these authors that caverns and galleries, as well as more or less vertical pits, are opened mainly by solution. Rock falls from roofs and walls help in the process of enlargement, but some of the fallen limestone debris is dissolved

as well as walls, floors, and even roofs. In any case mechanical erosion cannot attain any importance until after solution has enlarged joint cracks which were initially minute into passages sufficiently open to allow concentrated streams of water to flow through them with considerable velocity. It is obvious that some of the voluminous streams that are flowing on the floors of low-level caverns and are carrying loads of debris, part of it brought down from the surface, are capable of corrasion and that their actual channels have been to some extent shaped and enlarged mechanically; but tests have proved that underground flow is generally rather slow and rarely deserves the epithet "torrential". Thus it seems justifiable to set aside the process of mechanical erosion as subsidiary and possibly even non-essential, and to assume that caverns similar to, if not identical with, the caverns in which these streams flow can be produced by solution alone. It is not so much waste mechanically transported as carbon dioxide brought down from the surface in solution that the underground water makes use of as a tool for the process of excavation.

Patterns of Gallery Systems

Though enlarged vertical cracks, shafts, and high dome-shaped chambers are common also, many caverns have great horizontal extension as galleries, and the galleries are generally arranged in looped or netted systems spread over a wide area (Fig. 370). If, as is commonly the case, caverns are present at various depths, they are generally arranged in more or less regular tiers at successively deeper levels. Though not far in a general way from horizontal (with a few ups and downs) the galleries and tiers of chambers have some organised slope which allows, or seems in the past to have allowed, water to run through them in streams without many falls or rapids down gradients similar to those of small streams on the surface. Indeed, according to Meinzer,

the underground streams, like the surface streams, become adjusted to some base-level, such as the sea, a lake, or a major surface stream, into which they discharge, and they tend to become graded to this base-level by the laws of stream gradation. Thus in a karst region there is developed a sort of underground peneplain which bears a close relation in its genesis to a surface peneplain. . . . Underground

streams . . . commonly develop channels of low gradient, and low underground divides. (MEINZER.)[16]

The gradients lead down to the exits or debouchures to the open air, which are situated in or on the sides of valleys. This idea reproduces and goes even farther than Martel's conception of underground river systems that mimic those on the surface.[13]

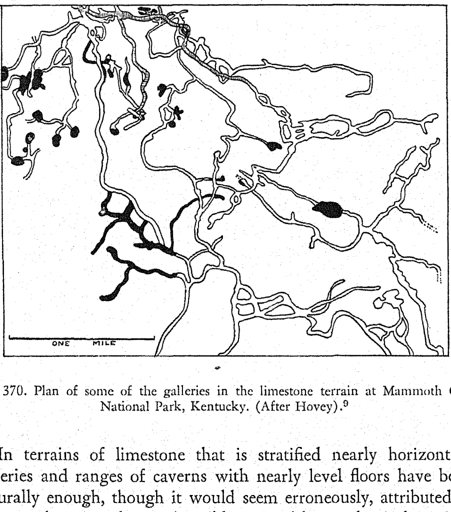

Fig. 370. Plan of some of the galleries in the limestone terrain at Mammoth Cave National Park, Kentucky. (After Hovey).[9]

In terrains of limestone that is stratified nearly horizontally galleries and ranges of caverns with nearly level floors have been, naturally enough, though it would seem erroneously, attributed by many authors to solution (possibly assisted by mechanical erosion) taking place along bedding planes, and it has been assumed that there must be present layers of relatively impermeable or insoluble rock underlying cavern floors. Diagrams embodying this theory and reproduced in various textbooks are based mainly on those published originally by Shaler[21] and Cleland.[1] This cannot be the general cause controlling such gradients, however, because similar cave-floor gradients are found where caverns intersect inclined and folded

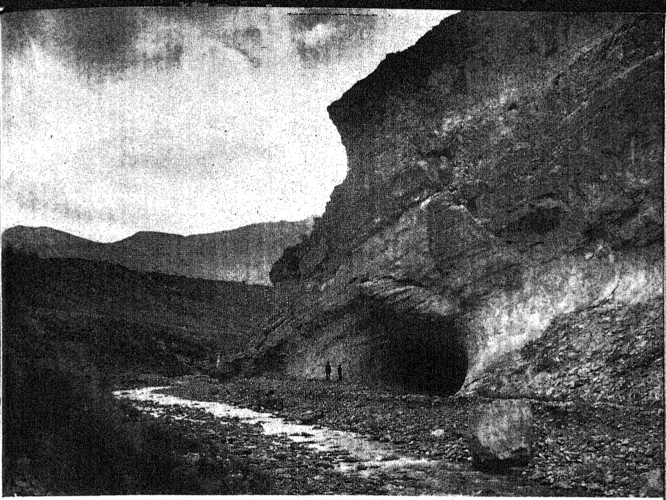

Photo from Professor R. Speight

Fig. 371. The entrance to a cavern and gallery at ground-water level in inclined limestone strata, Broken River basin, New Zealand.

limestone strata (Figs. 345, 371, 373). In caves in the Shenandoah Valley, Virginia, where the limestone is folded, "the larger chambers are developed at consistent levels, which cross the inclined layers at strong angles and suggest a control of solution by the former water table".[5] Where the limestone formations are of only moderate thickness it is naturally only in areas of horizontal bedding that systems of galleries of great lateral extent can be formed. Examples of extensive systems of caverns in horizontal and very gently inclined limestone strata are found in Kentucky, Indiana, and Tennessee. Underground river channels, abandoned at four successive levels, which are seen in the Jenolan caves, New South Wales, pass through a thick limestone stratum dipping at 60°.[24]

Some of the generalised ideal diagrams (e.g. Fig. 365, after Cvijić) that have been published in explanation of the landforms developed in limestone[14] indicate the presence of tiers of caverns that follow the dip in inclined strata, but in such diagrams the

necessary exaggeration of the vertical scale has caused the strata to be depicted in unnatural attitudes with exaggerated dips.

If unrelated to the bedded structure of the terrain, the gradients of the galleries are most probably either (*a*) developed in a manner analogous to the grading of surface streams or (*b*) related to the water table (i.e. to the level of the surface of the ground water which saturates the deeper rocks). In either case the galleries may be expected to lead such streams of water as flow (or might flow) on their floors towards a surface outlet, and in the general case they do drain out towards rivers in open valleys. All such rivers in a limestone terrain are fed in part by springs that originate in

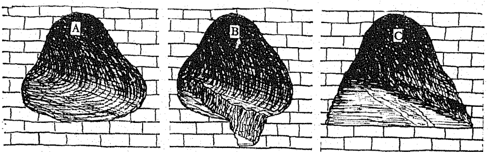

Fig. 372. A tubular gallery A, which has been opened by solution, may be enlarged by vertical corrasion, B, or lateral corrasion, C.

this way. The theory that mechanical erosion is mainly responsible for shaping galleries has been supposed to receive support from a more or less orderly arrangement and adjustment of their gradients which is commonly found.[13] Mechanical erosion (including both vertical and lateral corrasion) is capable of producing the tunnel form with a flat floor (Fig. 372, C) which some galleries assume,[5] and alteration of gradients as a result of vertical corrasion may be the correct explanation of some observed departures of gallery-floor profiles from accordance with bedding planes in gently inclined strata, though the initial channels formed by solution may have followed these. Many galleries, however, have roofs low enough in places to show that such mechanical erosion as has taken place in them has been lateral rather than vertical. Lobeck,[11] a believer in the efficiency of corrasion underground, regards its action as almost

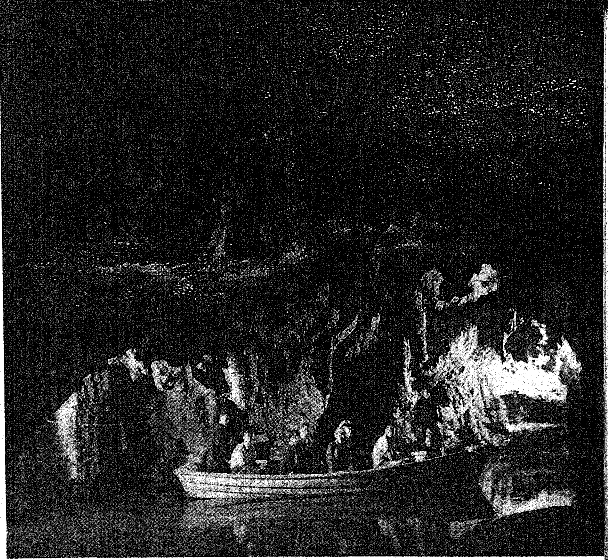

Photo from N.Z. Dep. Tourist and Publicity

Fig. 373. An underground river in the Glow-worm Cave, Waitomo, New Zealand.

entirely lateral in gallery cutting, and his generalised diagrams depict low-roofed, flat-floored, wide caverns so developed (compare Fig. 372). Davis[5] has pointed out also that the ground plan of galleries in cavern systems (Fig. 370) is generally very unlike that of river systems, and further that tributary or loop-forming galleries, in anastomosing systems, rarely join the main galleries at discordant levels (i.e. with hanging junctions). Possibly the celebrated glow-worm cavern at Waitomo, in New Zealand, through which an underground river flows (Fig. 373), is an exceptional example of a gallery considerably deepened by river work, for the cavern may be approached and viewed from a side gallery perched at a considerable height above the river. It is probable that this stream, which is sluggish, does much, or most, of the enlargement of its channel by corrosion.

Davis has indicated a possible method of grading of galleries without corrasional deepening:

Mature cavern streamlets in level strata develop their low-level stretches chiefly by the development of new shafts and of new galleries at lower and lower levels. [These are streamlets that have at an earlier stage of their existence resembled] certain small and young surface streams which cascade down the outcrops of resistant level strata and run for a considerable distance at a gentle slope on the intermediate weaker strata. (DAVIS.)[5]

The underground courses at the youthful stage have followed alternately vertical passages (enlarged joints) and horizontal passages dissolved out along bedding planes. Drainage of water through newly opened passages to lower levels leads to abandonment of the higher courses with zigzag descent before there has been time for their enlargement as galleries.

The foregoing hypotheses in explanation of the development of galleries are based on the assumption, which is very commonly made, that the water responsible for opening them up is "vadose", i.e. still descending through the unsaturated zone above the true ground water. When such water descends to the water table, as it has done when it is found flowing as considerable unbroken streams on the floors of the caverns of the lowest accessible gallery system, the fact has to be taken into consideration that either a seasonal or an unperiodic rise of ground water to a higher level may take place and completely fill the galleries. Thus may be introduced the hypothesis that graded systems of large galleries develop at or very close to the water table and below rather than above it, in which case the process of solution is mainly responsible for opening up the galleries and the slope of the water table determines their gradients—the alternative (*b*) referred to on p. 484.

A CAVERN ZONE AT THE WATER TABLE

The relation of the cavern zone to the water table has been pointed out by Grund[6] and Penck,[18] who have, however, ascribed some enlargement of fissures to solution below the water table also. The water-table development of a zone of caverns, which is traversed in this case by a river in an underground course, is well shown in diagrams which Penck has ascribed to Grund and which are here

copied as Fig. 374. These explain the origin of an underground course originating by superposition, as it were, on an anticline containing a limestone core, as is the case in some examples in Istria, notably the course of the River Foiba. When the course is first followed (above ground) across the anticline (A) the ground water (stippled) is close to the surface because the outcropping limestone is enclosed between belts of impermeable (non-limestone)

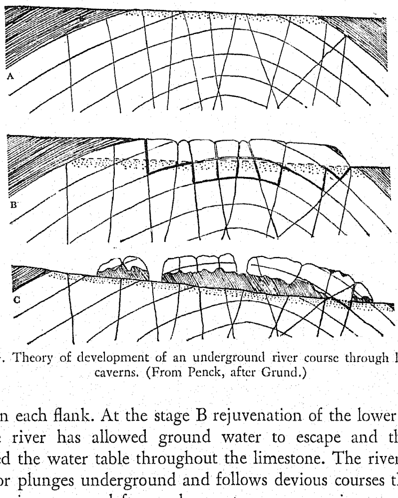

Fig. 374. Theory of development of an underground river course through limestone caverns. (From Penck, after Grund.)

rock on each flank. At the stage B rejuvenation of the lower course of the river has allowed ground water to escape and this has lowered the water table throughout the limestone. The river either leaks or plunges underground and follows devious courses through siphons in narrow clefts, as shown, to emerge again as a spring. After this (C) the lowering of the water table, which goes on progressively as the valley is deepened, allows vadose water to descend through and enlarge crevices, producing a characteristically sculptured surface (karst) on the limestone, and at the same time allows of an approach to a continuously graded condition in the underground course with the concomitant development of extensive caverns, necessarily high-roofed.

Theory of Solution far below the Water Table

A theory of the opening of caverns by ground-water solution definitely below the water table has been proposed by Grund,[7] and has been advocated especially by Davis.[5] Since the flow of ground water can take place at a considerable depth in some open-textured rocks, Davis has assumed that the development of galleries in limestone goes on far down in the saturated zone. In certain cases abundant underflow beneath river channels and leakage on a considerable scale from rivers into limestone strata are known to take place,[19, 23] and the underground passages thus entered by water may have been developed by solution below the water table. On the other hand, the water table may have risen recently to its present position in some such cases as a result either of earth movements or of the general rise of ocean level, thus flooding galleries that were opened at or above the water table. It seems improbable, however, that the ground water has thus risen in the Tennessee Valley, where Moneymaker[17] describes limestones cavernous to a very considerable depth below the beds of rivers that are flowing over bedrock. River-borne debris has entered and partly filled the caverns. These observations seem to indicate solution now in progress, though the openings below the water table are generally less extensive than those above it.

The limestone of the coastal plain of western South Australia is very cavernous near the surface, causing difficulty in drilling through it in search for water in underlying strata; but it is much less cavernous as the water table is approached. The water table, which is almost horizontal, is controlled by sea-level,[25] and has changed little since the coastal plain emerged except for temporary eustatic lowerings of the level of the ocean during such glaciations, if any, as have occurred since its emergence.

Some of the peculiarities of the holokarst region in Dalmatia result from a very wide seasonal fluctuation of the level of the water table[3, 6, 18] (Fig. 360). This fluctuation is perhaps attributable in part to a high annual rainfall combined with the Mediterranean condition of winter rain and summer drought, but it must be due in great part also to the small water-carrying capacity of such open channels as exist below the lowest (summer) level of the water

table, even where the terrain consists of limestone to some considerable depth below sea-level. Thus there seems to be little support in that region for a theory that the deep-lying limestone is riddled with caverns, though there are some passages through it which feed offshore springs of fresh water.

Few, if any, of the generalised diagrams that have been published by various authors to illustrate hypotheses of the relation of surface forms to underground passages indicate or suggest the presence of any caverns below the floors of the deepest valleys; but this is subjective and merely points to the influence of the theory of vadose origin.

The Water-table Theory Revived

Swinnerton[22, 23] disagrees with the opinion of Davis[5] that galleries are opened at a considerable depth. He regards the zone of the water table itself as that at which lateral movement of the ground water in limestone and also its activity in the excavation of galleries by solution are concentrated. Grund,[6] as quoted by Davis,[5] had earlier formed the opinion that caverns which are now dry had once been *at* the level of the karst water (ground water) and had been formed there by it.

Rhoades and Sinacori[20] conclude after discussion of theoretical considerations that deep flow and solution are possible in limestone, but that adjustment of ground-water flow to subsurface conditions tends to concentrate flow in the upper levels of the zone of saturation, so that eventually the most extensive galleries are developed at or very close to the water table "by the concentration of lateral flow through high-level master conduits". These "progressively enlarge and elongate in a headward direction".

The surface of the ground water becomes flat and nearly level when (but not before) numerous passages have been opened through the rocks, and thus it is possible to find a simple explanation of the grading of underground streams—the extension of Meinzer's "underground peneplain".[16] As the ground water sinks and its surface seeks lower and lower levels during the deepening of surface valleys, and the water table flattens and recedes from the valley walls,

joint zones, areas or beds of soluble rock, pre-existing openings, and other weaknesses of the rock localise the flow into channels. The larger of these channels extend themselves at the expense of small neighbouring channels. . . . The streams in the top of the water table develop eventually a normal gradient sloping gently upward from the level of the trunk surface drainage. The streams will branch throughout their course and will at length finger out and up into a fine-meshed network of slightly open joints, small caverns, and irregular intricate passageways (Swinnerton).[22]

The theory of development at the water table affords an explanation of the storied arrangement of galleries, for it may be assumed that the ground water sinks as valleys are deepened in successive geomorphic cycles and that new tiers of caverns are developed during the pauses in a discontinuous uplift of the region—i.e. whenever the water table sinks, becomes stabilised, and remains sufficiently long at any level. The upper tiers of caverns are no longer being enlarged, and it is in parts of these that dripstone deposits are accumulating (Fig. 375).

Karst Base-level Theory of Cvijić

Cvijić[3] pictures only one tier, or story, of caverns, which is developed, or at any rate is accessible, only where the base of the limestone—i.e. the contact with an underlying impermeable stratum —is above the floors of the river valleys. Though parallel to bedding, this zone of caverns is related not so much to the actual bedding as to a level at which water must move laterally after its descent from the surface. Such a zone, and the depth to which the water table can sink, are controlled in this case by the base of the limestone, or rather by the upper surface of the underlying relatively impermeable stratum. The latter Cvijić regards as furnishing in this way a base-level for the features developed by solution of the limestone. In those regions in which the limestone has beneath it other rocks, in which main valleys are incised, the theory of a local base-level for karst erosion at the base of the limestone is obviously useful. Rather inexplicably, however, Cvijić has attempted to apply it even in the holokarst territory, where the surface of other rocks below the limestone is far below sea-level. He asserts that sea-level does not control or in any way influence the flow of the main body

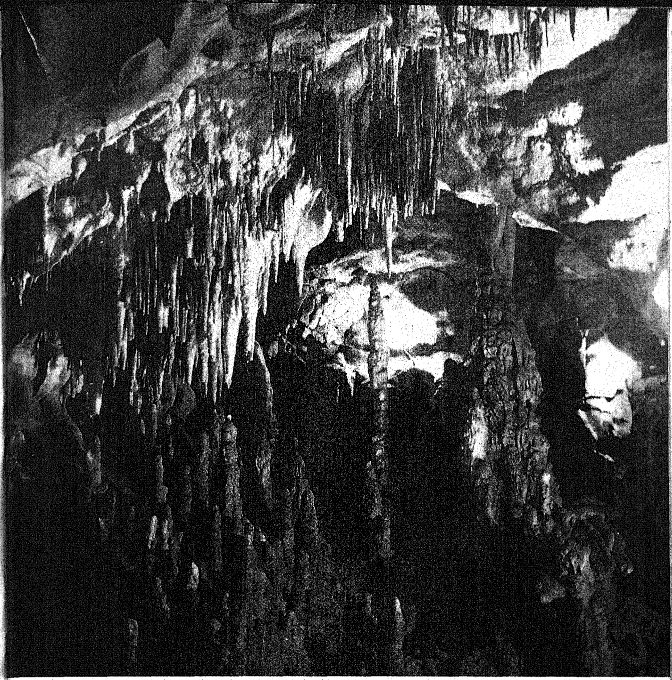

Fig. 375. Dripstone deposits, stalactites and stalagmites, partly filling a limestone cavern, Waitomo, New Zealand.

of ground water in the limestone terrain. (This water, indeed, following Grund,[6] he describes as "stagnant", though it appears that the description is not to be understood quite literally.) He pictures the ground water as everywhere descending vertically towards the base of the limestone, though the channels available for this descent are still very small at great depths, where, in his opinion, they have not yet been enlarged to any great extent by solution.

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